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Acoustic change complex for assessing speech discrimination in normal-hearing and hearing-impaired infants

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HIGHLIGHTS

- Acoustic change complex (ACC) to low-, mid-, and high-frequency speech stimuli can be recorded in awake infants with normal hearing and infants using hearing aids.
- ACC can be used to predict speech discrimination capacity in individual infants.
- ACC is positively correlated with parent-reported functional performance of infants in everyday life.

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ABSTRACT

Objective: This study examined (1) the utility of a clinical system to record acoustic change complex (ACC, an event-related potential recorded by electroencephalography) for assessing speech discrimination in infants, and (2) the relationship between ACC and functional performance in real life.

Methods: Participants included 115 infants (43 normal-hearing, 72 hearing-impaired), aged 3–12 months. ACCs were recorded using [szs], [uiu], and a spectral rippled noise high-pass filtered at 2 kHz as stimuli. Assessments were conducted at age 3–6 months and at 7–12 months. Functional performance was evaluated using a parent-report questionnaire, and correlations with ACC were examined.

Results: The rates of onset and ACC responses of normal-hearing infants were not significantly different from those of aided infants with mild or moderate hearing loss but were significantly higher than those with severe loss. On average, response rates measured at 3–6 months were not significantly different from those at 7–12 months. Higher rates of ACC responses were significantly associated with better functional performance.

Conclusions: ACCs demonstrated auditory capacity for discrimination in infants by 3–6 months. This capacity was positively related to real-life functional performance.

Significance: ACCs can be used to evaluate the effectiveness of amplification and monitor development in aided hearing-impaired infants.

Abbreviations: ACC, Acoustic change complex; ABR, Auditory brainstem response; AN, Auditory neuropathy; CAEPs, Cortical auditory evoked potentials; 95% CI, 95% confidence interval; dB A, A-weighted decibel; dB SPL, decibel Sound Pressure Level; EEG, Electroencephalography; 4FA in dB HL, Four-frequency average hearing level in decibel Hearing Level; HAs, Hearing aids; Hz, Hertz; HI, Hearing impairment; ICC, Intraclass correlations; kHz, kiloHertz; ms, millisecond; MMN, Mismatch negativity; NH, Normal hearing; PCHL, Permanent childhood hearing loss; PEACH, Parent's evaluation of aural/oral performance in children; sec, second; SRN, Spectral ripple noise.

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1. Introduction

Permanent childhood hearing loss (PCHL) has a negative impact on children's speech and language development, which could be ameliorated by implementing early detection via newborn hearing screening, early fitting of hearing devices and early intervention (Ching and Leigh, 2020; Fitzpatrick et al., 2007; Kennedy et al., 2006; Tomblin et al., 2015; Yoshinaga-Itano et al., 1998). For children who receive limited benefits from hearing aids (HAs), early cochlear implantation before 12 months of age has been linked to better language outcomes (Ching et al., 2017; Dettman et al., 2016). Cochlear implantation is standard care for children identified with profound hearing loss but not for those with lesser degrees of hearing loss, unless they demonstrate deficits in speech discrimination and language abilities with amplification (Gifford, 2013. p.7). Therefore, accurate assessment of speech discrimination capacity in individual infants with PCHL is critical for quantifying HA benefits to guide decisions about intervention choices, including cochlear implantation. The assessment tool for infants would ideally be an objective physiological measure that correlates with functional auditory skills (Small, 2015). What is currently lacking is a validated clinical tool that enables clinicians to identify infants who obtain limited benefits from HAs so that they can be referred early for implant candidacy evaluation. The current study was aimed primarily at filling this gap.

A viable method for assessing the neural bases of speech discrimination in infants is to use objective electroencephalography (EEG). Measurements of EEG, including speech-evoked auditory brainstem response (ABR, Hornickel et al., 2012, Skoe and Kraus, 2010), cortical auditory evoked potentials (CAEPs, Wunderlich and Cone-Wesson, 2006), mismatch negativity (Cheour et al., 1998), and acoustic change complex (ACC, Uhler et al., 2018) in infants and young children have been reported.

In awake infants and young children, CAEPs recorded from the vertex relative to one of the mastoids in response to stimuli presented at a rate of about one per second generally consists of a positive peak ranging from about 250 ms (at birth) to about 100 ms (in early childhood), followed by a low-amplitude negative deflection ranging from 450 to 600 ms at birth to about 200 ms in early childhood (Van Dun et al., 2012). A decrease in latency with age has been reported, which appears to be related to maturation of the auditory system and the duration of exposure to sound (Bauer et al., 2006; Ponton et al., 1996; Sharma et al., 2007). By measuring CAEPs elicited using speech stimuli ([m], [g], [t]) presented at 65 dB SPL (decibel Sound Pressure Level) in the sound field, Munro et al (2020) reported that in typically developing infants (age between 5 and 39 weeks), detection CAEPs in response to the three stimuli was 86%, 100% and 92% respectively. In infants with PCHL, the detection rate was associated with audibility supported by amplification in infants aged between 3 and 30 months (Chang et al., 2012; Van Dun et al., 2012). Clinical applications of this approach to encourage uptake of amplification after diagnosis (Munro et al., 2020), to evaluate HA fitting and to guide individual fine-tuning of HAs for infants (Punch et al., 2016) have been reported. Parents' acceptability of this approach as a clinical procedure is high (Mehta et al., 2019; Munro et al., 2020). Importantly, the clinical applicability of CAEPs for objective evaluation of the effectiveness of amplification has been confirmed by Golding et al. (2007). The study showed that a higher detection rate of objective CAEPs in children using HAs was positively associated with higher scores on functional auditory performance in real life, measured subjectively by parents completing the Parents' Evaluation of Auditory functional performance in Children or PEACH scale (Ching and Hill, 2007).

Detection is necessary, but not sufficient for discrimination. As sensitivity to acoustic cues that signal phonetic contrasts lays the foundation for language learning (Benasich et al., 2002; Werker and Tees, 1987), auditory discrimination is crucial in spoken language acquisition (Kuhl et al., 2005; Tsao et al., 2004). Previous studies have shown that CAEPs could be recorded in response to not only presence of sounds but also changes in signal intensity, pitch, timbre, phase and spectrum in an ongoing stimulus in adults. The electrophysiological response is referred to as an ACC (Dimitrijevic et al., 2009; He et al., 2012; Jones and Perez, 2001; Martin and Boothroyd, 1999; Ross et al., 2007).

Measurement of ACC provides insights into the brain's capacity to process the acoustic features of speech at the auditory cortex (Ostroff et al., 1998). In awake typically hearing infants aged between 4- and 7-months and adults, Small and colleagues (Small and Werker, 2012) recorded ACCs using consonant–vowel (C_1VC_2V) tokens as stimuli, with C_1 and C_2 being stop consonants that were either the same or different in terms of place of articulation ([dada], [daba], or [daDa] where [D] represents a retroflex stop). Whereas adults demonstrated ACCs to all stimuli, infants showed a consistent ACC only to the [ba] in [daba], but not other stimuli. The authors considered that the stimulus duration was too short to allow sufficient recovery from the onset response to the first syllable for infants. They demonstrated that ACC responses were more robust in infants when the duration of the stimuli was extended to 816 ms (Chen and Small, 2015). Strahm et al. (2022) measured ACCs using iterated rippled noise as stimuli, showing high variability in normal-hearing infants' below 16 months of age, but an increase in consistency and reliability by 22 months. In asleep normal-hearing infants aged 1.8–4.6 months, however, Uhler et al. (2018) reported that mismatch responses, rather than ACCs, revealed significant group-level differences to /a/ and /i/ stimuli. They cautioned that such differences could be difficult to identify at an individual level due to the large variability in individual participants (Bishop and Hardiman, 2010).

Current literature suggests that measurements of ACC and mismatch negativity are potential tools for evaluating discrimination in infants, with the former being applicable to awake and the latter to asleep infants. One advantage of measuring ACC over mismatch negativity in clinical applications is that the former elicits responses with larger amplitudes and better signal-to-noise ratios, thus requiring less time and fewer presentations than the latter for recording (Martin and Boothroyd, 1999). The better reliability, sensitivity and efficiency of ACC compared to mismatch negativity observed at an individual level suggest that measurements of ACC hold great potential to be used clinically for identifying infants who may have discrimination deficits with amplification (Bishop and Hardiman, 2010; Kim, 2015; Martin and Boothroyd, 1999; Tremblay et al., 2003). To assess discrimination in different frequency regions, ACCs need to be recorded using stimuli that are as frequency specific as possible, and that spans a wide range of speech frequencies (Van Dun et al., 2012). There are no studies that examined the feasibility of measuring ACC in infants with typical hearing and those with hearing loss using stimuli that target auditory processing of spectral changes in low-, mid- and high-frequency regions.

In clinical practice, a well-established method for subjectively evaluating the effectiveness of amplification for young children is to rely on parental observations and questionnaires (AAA, 2013; Bagatto et al., 2010). The PEACH is a parent-report measure of children's functional auditory and communicative performance in everyday life that has been incorporated in the National Pediatric Amplification protocol for evaluating effectiveness of amplification in Australia (King, 2010; Punch et al., 2016), and for validating the use of CAEPs for assessing audibility with amplification (Golding et al., 2007). The PEACH contains 13 items, two of which relate to background information about the child's usage of hearing device and listening comfort and are not used for scoring. The remaining 11 items solicit information about the child's auditory behaviour and communicative performance in quiet (five questions) and in noisy situations (six questions) in everyday life. Parents are asked to observe their child in everyday life to rate their auditory/oral behaviour in real-life situations on a scale of 0 to 4 using the PEACH rating scale. An overall total score on functional performance is calculated using the summed ratings of the 11 items. The Quiet and Noise subscale scores are calculated using the summed ratings of 5 items on listening in quiet situations and 6 items on listening in noisy situations respectively. The total score depicts the overall auditory functional performance of a child in different real-life situations. As such, the score is used for clinical evaluation of hearing aid effectiveness for young children. Normative data from normally hearing children aged 0.25 to 46 months and information about critical differences have been published for the questionnaire (Ching and Hill, 2007), and normative data showing the PEACH total score as a function of age have been published for the rating scale (Bagatto and Scollie, 2013). The present study examined the criterion validity of the objective measure of ACC in infants by comparing the rates of Onset and ACC with an established standard for evaluating aided functional performance in infants, the PEACH total scores based on ratings by parents.

The primary goals of this study were to (1) examine the utility of a clinical CAEP system to record ACC for assessing early-life speech discrimination in infants with PCHL using HAs; and (2) examine the relationship between objective speech discrimination and auditory functional performance in real life measured subjectively using the PEACH scale. Our specific research questions were as follows:

1. Can ACC to sound changes in low, mid, and high-frequency regions be reliably recorded in normal-hearing infants?
2. Can ACC to sound changes in low, mid, and high-frequency regions be reliably recorded in infants with hearing loss using HAs? If so, does HA experience influence the rates of Onset and ACC (i.e. the proportion of instances in which the electrophysiological responses are detected)?
3. Does the objective measurement of onset and ACC in hearing-impaired infants correlate with their functional auditory performance in real life as reported by parents?

In line with findings from the literature, we hypothesized that (1) ACCs can be elicited by acoustic changes at different frequencies in normal-hearing infants; (2) that ACCs can be recorded in infants with hearing loss using HAs, but the rates of onset and ACC decrease with increase in hearing loss. Further, for the same degree of hearing loss, a proportion of infants would show responses to Onset but not ACC, but the proportion is unknown. Also, the influence of HA experience on the response rate of CAEPs in infants is unknown. We also hypothesized that (3) infants with higher rates of Onset and ACC have better functional auditory performance in real life as measured by the PEACH total score.

2. Methods

2.1. Participants

One hundred and fifteen infants, comprising 72 with hearing impairment (HI; 40 female, 32 male) and 43 with normal hearing (NH; 19 female, 24 male) participated in this study.

Families of infants diagnosed with significant bilateral hearing loss through universal newborn hearing screening who presented at Hearing Australia, the national hearing service provider for all children with hearing loss in Australia, were invited to participate in this study. To be eligible, infants needed to be between 3 and 12 months of age, with no additional disabilities that may influence their development. Etiology was not a selection criterion as its effect is beyond the scope of the present study. The infants were fitted with HAs by audiologists using the National Acoustic Laboratories prescription for nonlinear hearing aids, version 2 (Dillon et al., 2011) according to a national protocol (King, 2010). A comparison group of 43 infants of the same age range who passed newborn hearing screening participated to provide normative data. The Australian Hearing Human Research Ethics Committee approved the protocols used in the study. Written informed consent for participation was obtained from parents of infants.

2.2. Study procedure

Following enrolment in the study, infants who were enrolled before 6 months of age were tested firstly around 3 – 6 months of age, and then again at 7 – 12 months of age. Infants that enrolled after 6 months of age were evaluated once only. For HI participants, these assessment time intervals corresponded to around 6 weeks after initial fitting of HAs, and then about six months post-fitting. Chart reviews were conducted to collect audiological information and hearing levels of the HI participants from the hearing service provider. Parents completed written questionnaires to provide demographic information (see Table 1). Prior to cortical assessments at 7 – 12 months, parents were asked to complete the PEACH rating scale, based on observations of their child's auditory/oral performance in everyday life situations over one week.

2.3. EEG procedure

Cortical responses were acquired using the HEARLab^{TM} (Frye Electronics, Tigard, OR, USA), a commercially available evoked potential system designed for clinical use (Van Dun et al., 2015). This system is a two-channel recording device, with the first channel recording Cz-M1 and the second channel recording Cz-M2. Four electrodes were used for EEG recording. Electrode sites were prepared using a cotton applicator and electrode gel. Single-use Ambu Blue Sensor NTM self-adhesive electrodes were placed at Cz (non-inverting electrode), left and right mastoid (M1 and M2, inverting) and forehead (Fpz, ground). The electrodes were held in place using a soft elastic headband. Electrode impedance was checked, and the preparation was repeated if required to ensure that inter-electrode impedances were less than 5 kΩ.

During EEG recording, the participant was seated on their parent's lap in a sound-treated booth. A researcher used distractions such as age-appropriate toys or silent movies to encourage the participant to sit quietly in the test position. The audiologist monitored the child's arousal state throughout the data acquisition period to ensure that the child remained awake and alert during testing, and that the position/ impedance of the electrodes on the child remained stable to maintain good quality recording. The data acquisition system and test procedure aligned with clinical practice currently in use for cortical assessments at hearing service centres in Australia (Punch et al., 2016), so that the findings have direct implications for clinical utility.

2.4. EEG stimuli

The test stimuli were [uiu], [szs], and an SRN high-pass filtered at 2 kHz (kilohertz) (see Fig. 1). These stimuli were selected to assess sensitivity to acoustic changes in specific frequency regions respectively, and together, to span the speech range from low to

Table 1
Demographic characteristics of participants.

Characters	Interval 1 (age 3–6 months) (n = 74)		Interval 2 (age 7–12 months) (n = 91[#])	
	Hearing impaired (HI)	Normal Hearing (NH)	Hearing impaired (HI)	Normal Hearing (NH)
Number of participants	52	22	52[$]	39[*]
Gender (Male): n (%)	27 (51.9%)	12 (54.5%)	24 (46.2%)	23 (59.0%)
Age at assessment (months)				
Mean (SD)	4.8 (1.0)	4.5 (1.2)	10.7 (1.6)	9.9 (1.6)
Median	5.0	4.5	10.5	10.0
IQR	4.0–6.0	3.0–5.8	9.8–12.0	9.0–11.5
Native Language: n (%)				
English	40 (76.9%)	19 (86.4%)	41 (78.8%)	34 (87.2%)
Other	10 (19.2%)	3 (13.6%)	11 (19.2%)	4 (13.6%)
Missing data	2 (3.8%)	0	0	1
Maternal Education: n (%)				
University Qualification	33 (63.5%)	20 (90.9%)	38 (73.1%)	34 (87.2%)
Other	17 (32.7%)	2 (9.1%)	14 (32.7%)	5 (9.1%)
Missing data	2 (3.8%)	0	0	0
Hearing Loss[@]: n (%)				
Mild (≤40 dB)	19 (36.5%)	NA	19 (36.5%)	NA
Moderate (41–60 dB)	20 (38.5%)		26 (50.0%)	
Severe (61–80 dB)	9 (17.3%)		7 (13.5%)	
Profound (>80 dB)	4 (7.7%)		0	
Age at HA fitting (months)				
Mean (SD)	1.9 (0.6)	NA	2.1 (0.9)	NA
Median	1.7		1.8	
IQR	1.5–2.3		1.5–2.4	

[#]Included 50 participants from Interval 1. [$]32 also participated in Interval 1; [*]18 also participated in Interval 1. [@]Averaged hearing threshold levels at 0.5, 1, 2, and 4 kHz in the better ear (4FA) in dB HL (decibels hearing level).
Note: Standard deviation: SD; IQR: inter-quartile range.

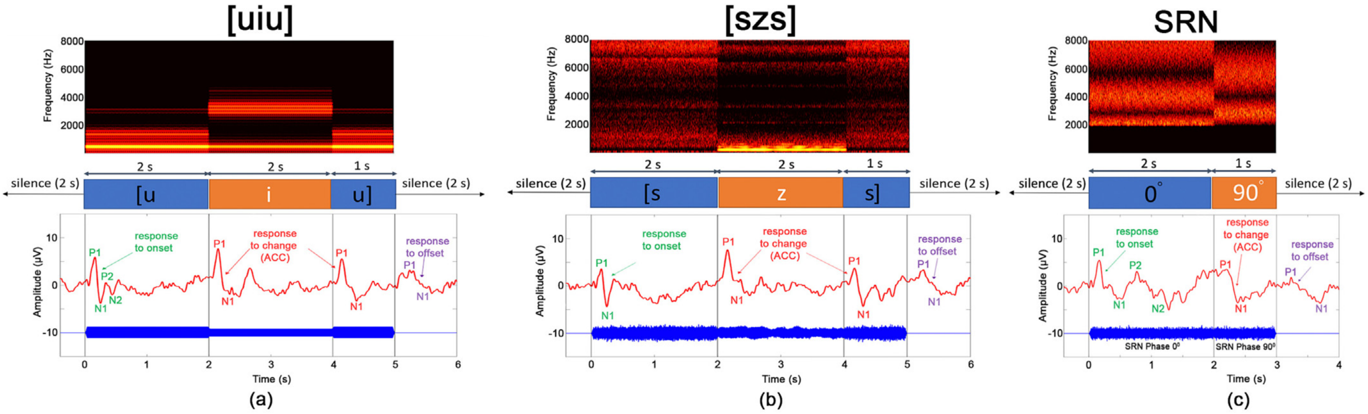

Fig. 1. The spectrographic display of the stimuli and the EEG recording showing responses to the Onset, Acoustic change complex (ACC) and offset for each stimulus ([uiu], [szs], and high-pass filtered spectral rippled noise (SRN)).

high frequencies so that responses at different frequency regions across the range can be used to guide hearing rehabilitation. The stimulus [uiu] was synthesized using a fundamental frequency of 221 Hz (Hertz). For [i], the formants one and two were 280 Hz and 2300 Hz respectively. For [u], the formants one and two were 380 Hz and 1250 Hz respectively (Cox, 1996). This stimulus was used to assess sensitivity to acoustic changes at mid frequencies. The [szs] stimulus was produced by a female adult native speaker of English, comprising a sustained [s] for 2 sec (seconds) followed by a sustained [z] for 2 sec and then a sustained [s] for one sec. This stimulus assesses sensitivity to acoustic changes at low frequencies (voicing). The SRN was created by superposition of 4000 sinusoids equally distributed on a logarithmic scale over a bandwidth between 2.0 and 11.2 kHz. This stimulus was used to assess sensitivity to acoustic changes at frequencies above 2 kHz. The spectral modulation starting phase for the ripple was randomly selected from a uniform distribution (0 to π rad), with one ripple per octave and a modulation depth of 20 dB (relative to 100% modulation). The total duration of the SRN was 3 sec, with a phase shift occurring at 2 sec after onset of the stimulus. To avoid spectral leakage at the transition, each stimulus was windowed with a 40 ms (milliseconds) rise-fall ramp, and the stimuli were concatenated with a 20 ms overlap. The interstimulus interval was 2 sec.

Using a head and torso simulator (Brüel and Kjær, Nærum, Denmark, https://www.bksv.com/en), all stimuli were equalized in loudness at 20 sones using the loudness model of Moore and Glasberg (2007). The equivalent dB SPL and dBA (A-weighted decibel) necessary to achieve a loudness level of 20 sones are shown in Table 2.

2.4.1. Stimulus presentation

Prior to testing of participants, otoscopy and tympanometry were conducted using standard audiological procedures. All measurements of CAEPs for infants with hearing loss were carried out in the aided condition, with HAs set at personal settings. The

Table 2
Sound level recorded at a distance of 1 metre of the loudspeaker at 0° azimuth in dB SPL (decibel Sound Pressure Level) and dBA (A-weighted decibel) to achieve a loudness of 20 sones for all stimuli of the experiment and for the pink noise used to calibrate the system.

Stimuli	Sones (ANSI S3.4-2007)	dB SPL	dB A
[u]	20	71.5	67.5
[i]	20	68.0	68.0
[s]	20	64.5	63.0
[z]	20	70	61.5
SRN 1	20	68.5	69.0
SRN 2	20	68.5	69.0
Pink Noise	20	62.0	61.0

HAs were measured in a standard coupler (HA2-2cc) to confirm that they were functioning, and batteries were replaced.

Stimuli were presented from a loudspeaker positioned at 0° azimuth at one metre. Before EEG recording, calibration was performed using a half-inch Brüel and Kjaer microphone so that stimuli were presented at 20 sones (approximately 65 dB SPL) at the test position, with the subject absent. Stimuli presentation and data acquisition were controlled using the HEARLab^{TM} system.

The stimuli were presented in a fixed order, [uiu], SRN, and lastly [szs]. The order of presentation aligned with normal speech acquisition in infants that progresses from phonetic contrasts relating to voicing and vowel formant patterns before high-frequency spectral information (Fourcin, 1980). The EEG data were acquired using the HEARLab^{TM} system at a sampling rate of 16 kHz and quantized in 16-bit. During data acquisition, the number of epochs and the level of residual noise were closely monitored by an audiologist. Where possible, each stimulus was presented until 160 epochs were accepted with residual noise level below 2.5 μV.

2.4.2. Data processing

Processing of EEG data was completed offline using a custom-designed MATLAB program. The EEG data collected using the HEARLab^{TM} system were exported for processing, down-sampled to 1000 Hz, and then low-pass filtered at 30 Hz. Then, the EEG recordings were segmented into 900 ms epochs, each comprising a 200 ms pre-stimulus baseline and a 700 ms post-stimulus onset segment. An artifact rejection algorithm was then applied to exclude any epoch that had a maximum absolute value greater than 160 μV or a mean epoch value greater than 60 μV. The epochs from the left and right mastoid channels were then combined by using a weighted averaging process. The weights were calculated based on the epoch's variance from each of the electrode site. The variance of each electrode site can be formulated as:

$$\sigma_i^2 = \frac{1}{901}\sum_{n=-200}^{700}\left(s_i(n) - \bar{s}_i\right)^2 \tag{1}$$

where i was the index which determined whether it was the left or the right mastoid site and $s(n)$ was the epoch's EEG value at time sample n. The combined weighted average can then be formulated as:

$$s_c(n) = \left(\frac{\sigma_2^2}{\sigma_1^2+\sigma_2^2}\right)s_1(n) + \left(\frac{\sigma_1^2}{\sigma_1^2+\sigma_2^2}\right)s_2(n) \tag{2}$$

In cases where only one site epoch was accepted, $s_c(n) = s_a(n)$ where $s_a(n)$ was the accepted site.

Analyses using the Hotelling's T^2 statistic (Flury and Riedwyl, 1988) were applied to determine the presence of a cortical response elicited by the onset of a stimulus or detection (hereafter referred to as the 'onset' response), the two ACCs in response to the change of the stimulus or discrimination (contrasts in both directions; referred to henceforth as 'ACC1' and 'ACC2'), and the offset CAEP. For the SRN contrast, the responses consisted of the onset, ACC1 and offset. The p-value calculated from the Hotelling's T^2 indicates the probability that the response is significantly different from zero (i.e. is not just background EEG noise uncorrelated with the signal). The statistic has been shown previously to detect cortical response waveforms with a combined sensitivity and specificity that was better than that achieved by expert human observers (Golding et al., 2009). Response presence ($p < 0.05$) was determined for each stimulus and each participant. The p-values were used to compute z-scores.

To assess the within-session test–retest reliability of CAEP recordings in infants, intraclass correlations (ICC) were used for comparisons within the waveform from −200 ms to 700 ms for each stimulus. The accepted epochs from each participant and each stimulus contrast were sub-divided into two data sets: the accepted odd number epochs were placed in group A, and the even number epochs were placed in group B. The averaged epochs from group A and group B were then calculated by ICC, formulated as

$$r = \frac{\sum_{n=-200}^{700}A(n)B(n)}{\sqrt{\sum_{n=-200}^{700}A^2(n)}\sqrt{\sum_{n=-200}^{700}B^2(n)}} \tag{3}$$

where $A(n)$ and $B(n)$ were the averaged epoch waveform from groups A and B at sample n. This correlation coefficient index represents the similarity between data in the two groups. A high correlation value indicates that the response is highly repeatable and unlikely to be due to random noise. The ICC calculation was performed for cases where more than 160 epochs were accepted and CAEP responses were present.

2.5. Parent-rated auditory functional performance of children

The PEACH rating scale was sent to parents one to two weeks prior to cortical testing. They were asked to observe their child's auditory behaviour in everyday situations and rate their performance. The completed scales were collected on the day of testing. Total scores, and Quiet and Noise subscale scores were calculated. The scores were then subtracted from the age-appropriate normative data for PEACH performance (Ching and Hill, 2007) to create relative PEACH scores for each participant. As the PEACH scores increase with increasing age, the use of the relative PEACH scores in this study provided for a comparison of cortical outcomes and performance on the PEACH scale with minimal influence of age as a confounding factor.

2.6. Statistical analysis

Rates of onset and ACC based on probabilities calculated by Hotelling's T^2 statistic were summarised using descriptive statistics, separately for infants with normal hearing and those with different degrees of hearing loss. Grand mean averages of EEGs were calculated across individuals for each stimulus at each test interval, separately for NH and HI participants. Analysis of variance (ANOVA) was performed using rates of responses as dependent variables with stimuli (3 stimuli) and response type (Onset vs ACC) as repeated measures, and hearing level (4 categories: NH, mild, moderate, severe-profound; based on averaged hearing threshold levels at 0.5, 1, 2 and 4 kHz in the better ear) and test interval (interval 1 at 3–6 months and interval 2 at 7–12 months) as categorical variables. Post-hoc analyses using Bonferroni tests were performed for significant interactions. Test-retest reliability was estimated by calculating ICC using a split-half method. Product moment correlation analyses were used to examine the relationship between CAEP outcomes (rates of Onset and ACC) and

PEACH rating scores. Results for all analyses were considered statistically significant at $p < 0.05$.

3. Results

Complete sets of EEG data for all 3 stimuli were recorded for a total of 61 infants at 3–6 months of age (20 NH, 41 HI), and 75 infants at 7–12 months of age (33 NH, 42 HI). Of these, 38 infants (15 NH, 23 HI) provided complete sets of data for all stimuli at both intervals. On average, assessments for interval 2 occurred 5.8 months (SD = 1.5) after interval 1. In addition, 13 infants completed recordings for one or two stimuli at 3–6 months of age (2 NH, 11 HI), and 16 infants completed recordings for one or two stimuli at 7–12 months of age (10 NH, 6 HI). Fig. 2 shows the grand average waveforms of all participants for each stimulus at the two assessment intervals. Fig. 3 shows the z-scores for Onset and ACCs of each stimulus at each assessment interval, as a function of four-frequency average hearing level in decibel Hearing Level (4FA in dB HL) in the better ear.

Reliability of CAEP recordings of participants for each stimulus was examined using intraclass correlation analysis. ANOVA using correlation coefficients as dependent variables, response type (onset vs ACC) as repeated measures, and hearing group (NH vs HI) and stimulus (3 stimuli) as categorical variables revealed an interaction between response type and hearing group (F (1,92) = 11.53, p = 0.001) for assessments carried out at 3–6 months. Post-hoc analysis showed that in HI participants, reliability was significantly higher (p = 0.001) for onset (Mean: 0.75; SD: 0.21; 95% confidence interval or 95% CI: 0.70, 0.80) than for ACC (Mean: 0.60; SD: 0.30; 95% CI: 0.53, 0.67). In NH participants, however, the mean correlations for onset (Mean: 0.66; SD: 0.28) and ACC (Mean: 0.77; SD: 0.24) were not significantly different (p = 0.39). The analysis was repeated for assessments completed at age 7–12 months, showing a main effect of response type (F (1,116) = 10.19, p = 0.002). On average, the correlation for onset responses (Mean: 0.65; SD: 0.25; 95% CI: 0.60, 0.70) was higher than that for ACC (Mean: 0.54; SD: 0.27; 95% CI: 0.49, 0.59). There were no other significant main effects or interaction.

3.1. Normal hearing infants

Fig. 4 shows the mean rates of Onset and ACC for each stimulus, separately for four groups based on hearing levels (normal, mild, moderate, severe-profound). Onset responses to all stimuli were

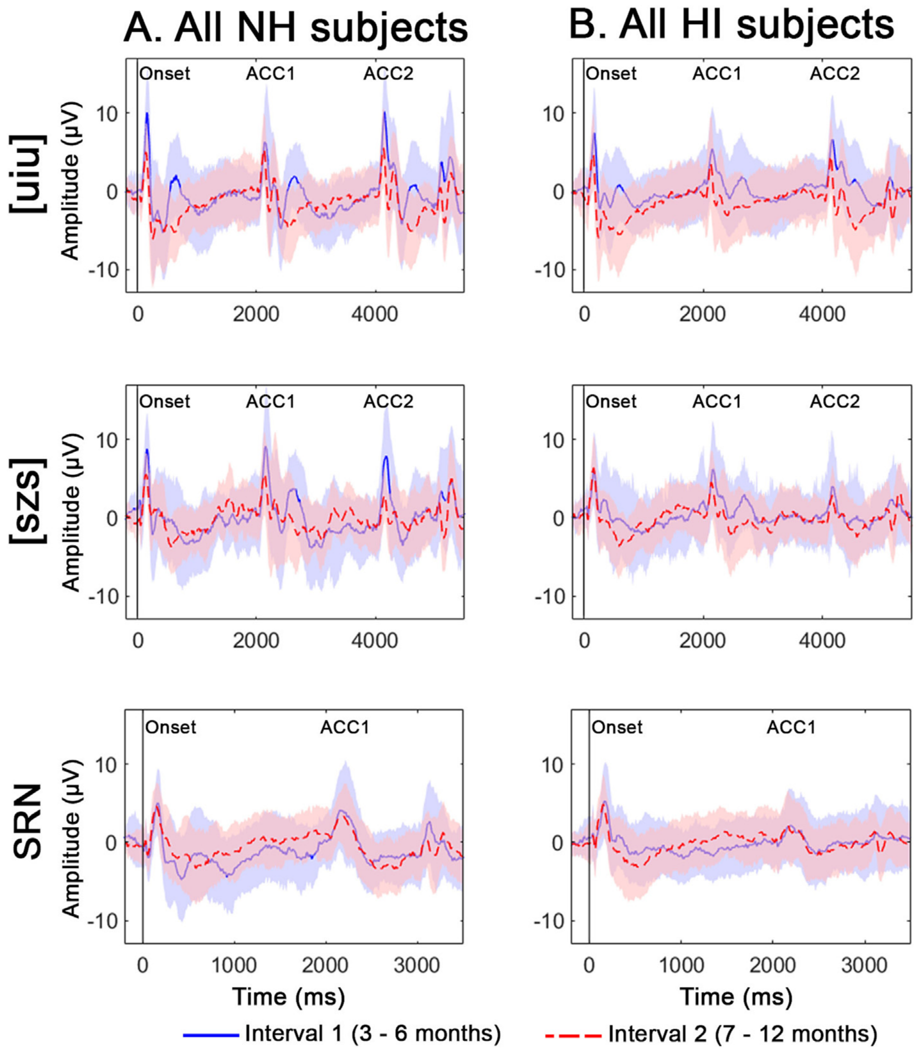

Fig. 2. Grand average waveforms across individuals for each stimulus: [uiu], [szs], and spectral rippled noise or SRN at test interval 1 (age 3 – 6 months) and 2 (7-12 months); separately for normal-hearing (NH) and hearing-impaired (HI) participants. In each panel, the blue line depicts the mean waveform, and the blue shaded area depicts +/- one standard deviation for responses collected during the first test interval. The red line depicts the mean waveform for responses collected during the second test interval. The labels "Onset", "ACC1" and "ACC2" refer to the cortical responses elicited by the onset of a stimulus, the first change in spectrum (e.g. from [u] to [i] in the stimulus [uiu]), and the second change in spectrum (e.g. from [i] to [u] in [uiu]) respectively. Panels in column A show mean waveforms for 43 NH infants, and panels in column B show mean waveforms for 72 hearing-impaired infants.

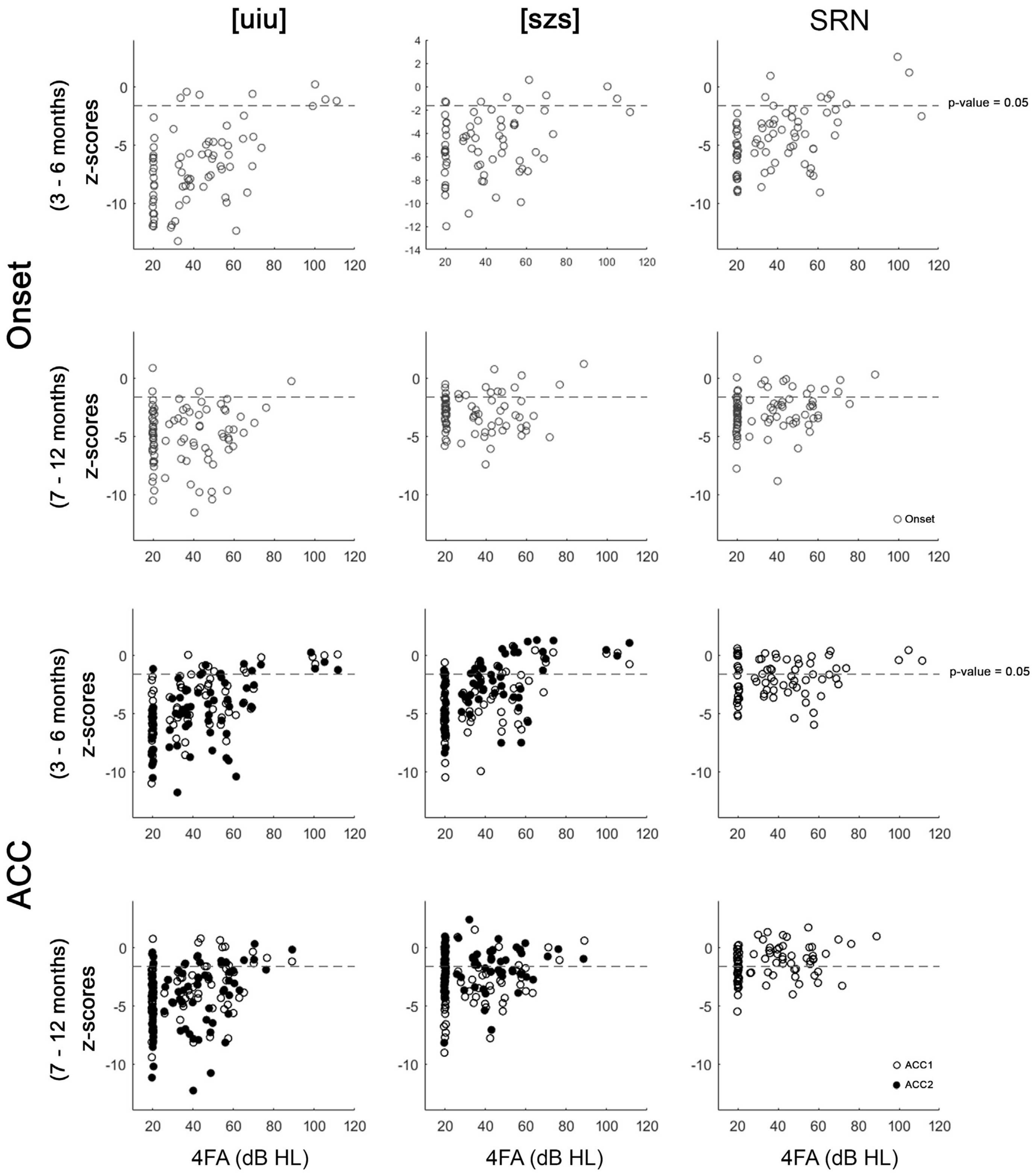

Fig. 3. Z-scores as a function of four-frequency average hearing level in decibel Hearing Level (4FA in dB HL) in the better ear. In each graph, the horizontal broken line at a z-score of −1.64 delineates a *p*-level of 0.05. Data points below the broken line depict responses that were significant at $p < 0.05$. From left to right, the graphs show responses for the stimuli [uiu], [szs], and high-pass filtered spectral rippled noise (SRN). From top to bottom, the graphs show z-scores for Onset at 3–6 months, Onset at 7–12 months, Acoustic change complex or ACC at 3–6 months, and ACC at 7–12 months of age.

present in 100% of cases assessed at 3–6 months, and >94% of cases assessed at 7–12 months of age. ACCs were present for ≥95% for [uiu] and [szs], and 64% for the SRN at 3–6 months; and 97% for [uiu], 76% for [szs], and 53% for the SRN for assessments at 7–12 months. Table 3 shows the rates of Onset and ACC for the 15 NH participants who completed cortical assessments for all stimuli at both time intervals. On average, there was no significant difference in the rates of Onset and ACC for [uiu] and SRN between test

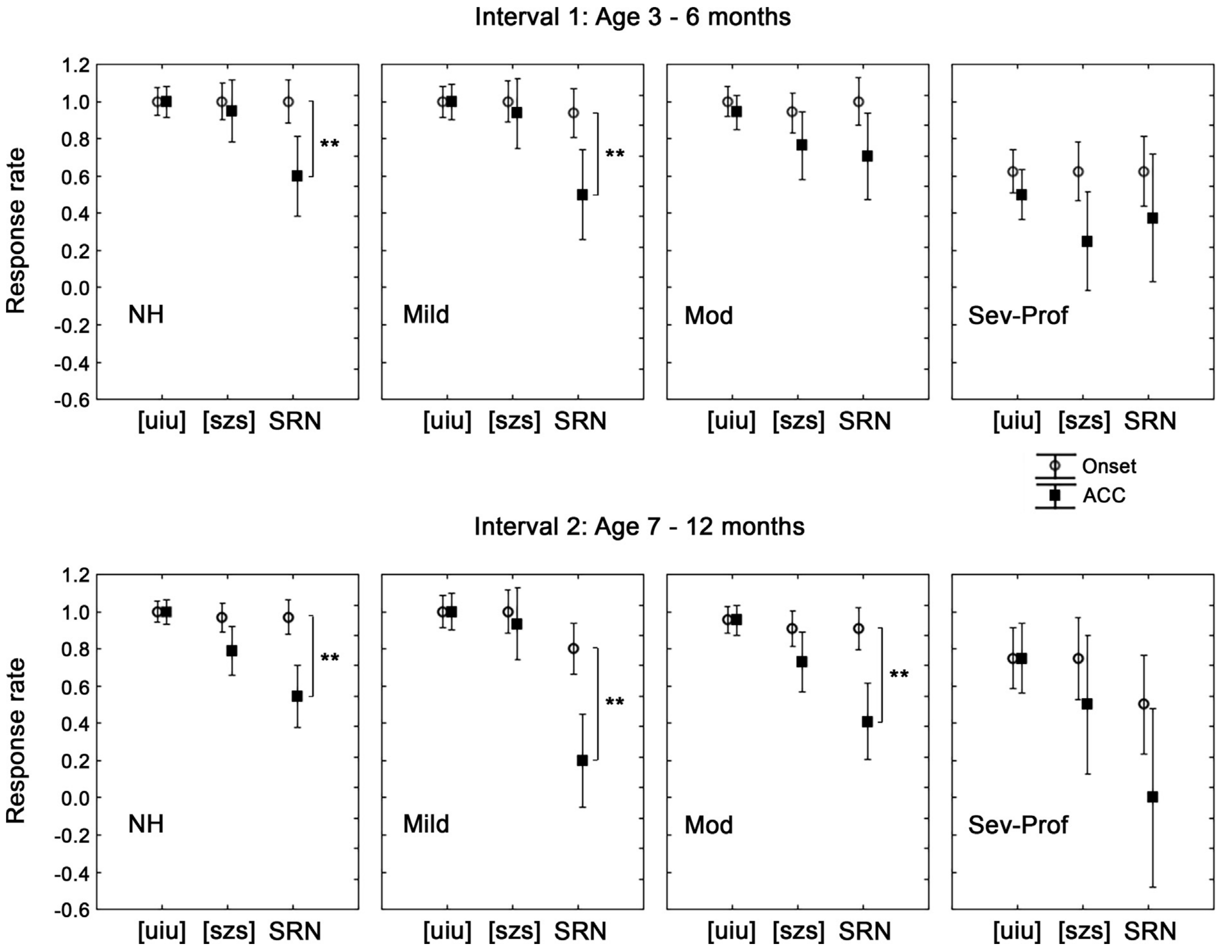

Fig. 4. Overall mean rates of Onset (open symbols) and Acoustic change complex or ACC (filled symbols) for the three stimuli [uiu], [szs], and high-pass filtered spectral rippled noise (SRN). Vertical bars denote 95% confidence intervals. The top row shows results obtained at age 3 – 6 months for infants with normal hearing (NH), mild hearing loss (MILD), moderate hearing loss (MOD), and severe-profound hearing loss (SEV-PROF) respectively in panels from left to right. The bottom row shows results obtained at age 7 – 12 months. In each panel, differences between Onset and ACC rates for the same stimulus that are significant at $p < 0.0001$ are marked by **.

Table 3
Rates of Onset and Acoustic Change Complex (ACC) for 15 normal-hearing participants who completed cortical assessments of all stimuli at interval 1 (age 3–6 months, T1) and interval 2 (age 7–12 months, T2). Significance at 5% level was marked by an asterisk.

	Interval 1 (3–6 mos)		Interval 2 (7–12 mos)		T1 – T2		*p*-level	
Stimuli	Onset	ACC	Onset	ACC	Onset	ACC	Onset	ACC
[uiu]	1.000	1.000	1.000	0.933	0.000	0.067	1.00	0.29
[szs]	1.000	0.933	1.000	0.600	0.000	0.333	1.00	0.03*
SRN	1.000	0.533	0.933	0.533	0.067	0.000	0.31	1.00

intervals, but the rate of ACC responses was significantly higher at interval 1 (age 3–6 months) than at interval 2 (age 7–12 months) for [szs]. Table 4 shows that 73% (27 of 37 responses) of ACC responses present at interval 1 were also present at interval 2. Of those who did not have ACC responses at interval 1, 38% (10 of 37) had ACCs at interval 2.

Table 4
Consistency in Acoustic change complex (ACC) responses between interval 1 (age 3 – 6 months) and interval 2 (age 7–12 months) for 15 normal hearing participants. Entries in the diagonal cells (bold text) indicate consistent responses between intervals 1 and 2.

		Interval 2		
		Present	Absent	Total
Interval 1	Present	**27**	10	37
	Absent	3	**5**	8
	Total	30	15	45

Table 5
Rates of Onset and Acoustic Change Complex (ACC) for 23 hearing-impaired participants who completed cortical assessments of all stimuli at interval 1 (age 3–6 months, T1) and interval 2 (age 7–12 months, T2).

	Interval 1 (3–6 mos)		Interval 2 (7–12 mos)		T1 – T2		*p*-level	
Stimuli	Onset	ACC	Onset	ACC	Onset	ACC	Onset	ACC
[uiu]	1.000	0.957	0.957	0.957	0.043	0.000	0.31	1.00
[szs]	0.957	0.826	0.957	0.870	0.000	−0.043	1.00	0.68
SRN	0.957	0.609	0.826	0.348	0.130	0.261	0.16	0.08

3.2. Infants with hearing loss

The rates of Onset and ACC for each stimulus for infants with different degrees of hearing loss are shown in Fig. 4. Table 5 shows the rates of Onset and ACC for the 23 HI participants that completed cortical assessments for all stimuli at both time intervals. On average, there was no significant difference in the rates of Onset or ACC for any of the stimuli across time (age at assessment and HA experience). Table 6 shows that 80% (44 of 55 responses) of ACCs present at interval 1 were also present at interval 2. Of those who did not have ACCs at interval 1, 36% (11 of 55) had ACCs at interval 2.

3.3. Effect of hearing level, stimuli, and assessment interval

ANOVA of response rates showed that there were significant main effects of hearing level (F (3,127) = 14.83, $p < 0.0001$); stimulus (F (2, 254) = 35.93, $p < 0.0001$); and response type (F (1,127) = 77.77, $p < 0.0001$). The effect of assessment interval was not significant ($p > 0.05$). There were significant interactions between stimulus and hearing level (F (6, 254) = 2.31, $p < 0.05$). Post-hoc analyses revealed that response rates in the severe-profound group were significantly lower than in the normal hearing group ($p < 0.001$) for all stimuli, the mild hearing loss group ($p < 0.001$) for [uiu] and [szs]; and the moderate hearing loss group ($p < 0.0001$) for all stimuli. Also, the interaction of stimulus and response type was significant (F (2,254) = 31.51, $p < 0.0001$). Post-hoc analyses showed that on average, the rate of Onset was higher than ACC for [szs] ($p < 0.0001$) and SRN ($p < 0.001$), but not for [uiu] ($p > 0.05$). The rate of ACC was higher for [uiu] than for [szs] ($p < 0.0001$) and SRN ($p < 0.001$). The rate of ACC for [szs] was higher than that for SRN ($p < 0.01$).

3.4. Relationship between objective ACC and functional performance in real life

The correlation between rates of ACC and the PEACH total score ($r = 0.37$, $p < 0.001$) showed a positive association. The correlation between rates of Onset and the PEACH total score ($r = 0.44$, $p < 0.001$) also showed a positive association. These coefficients were not significantly different ($p = 0.59$). In a similar vein, rates of ACC were significantly correlated with the PEACH Quiet score ($r = 0.37$, $p = 0.001$) and the PEACH Noise score ($r = 0.31$, $p = 0.004$). Also, the rates of Onset were significantly correlated with the PEACH Quiet score ($r = 0.39$, $p < 0.001$) and the PEACH Noise score ($r = 0.38$, $p < 0.001$).

The correlation between the combined Onset and ACC responses (maximum of 6) with PEACH scores was significant ($r = 0.44$, $p < 0.0001$). The correlations between the combined Onset and ACC responses and the PEACH Quiet score ($r = 0.41$, $p < 0.001$) and the PEACH Noise score ($r = 0.37$, $p < 0.001$) were also significant. As shown in Fig. 5, better functional performance measured by the parent-report PEACH scale was associated with an increase in CAEP outcomes.

Table 6
Consistency in Acoustic change complex (ACC) responses between interval 1 and interval 2 for 23 hearing-impaired participants. Entries in the diagonal cells (bold text) indicate consistent responses between intervals 1 and 2.

		Interval 2		
		Present	Absent	Total
Interval 1	Present	**44**	11	55
	Absent	5	**9**	14
	Total	49	20	69

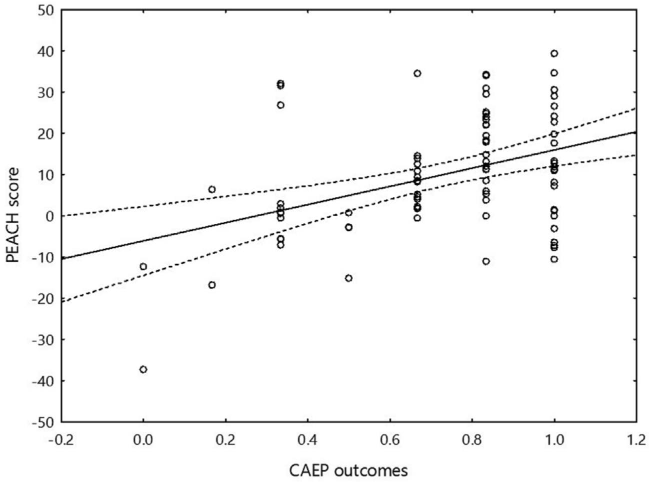

Fig. 5. Cortical Auditory Evoked Potential (CAEP) outcomes and total score of the Parents' Evaluation of Auditory functional performance in Children or PEACH scale. CAEP outcomes represent the number of event-related potentials recorded by electroencephalography, including Onset responses and Acoustic Change Complex, expressed as a proportion of a maximum of 6. The PEACH score is the summed ratings of 11 items, based on a parent-report measure of children's functional auditory and communicative performance in everyday life, expressed as age-corrected scores. The solid line is the regression line, and broken lines denote 95% confidence interval.

4. Discussion

4.1. Onset and ACC

The purpose of this study was to assess CAEPs for Onset and ACC in response to stimuli with spectral changes in low, mid, and high frequencies in awake infants with normal hearing and infants with hearing loss using HAs. CAEP responses to three stimuli were measured using a clinical evoked potential system (HEARLab; Frye Electronics, Tigard, OR), and responses to the Onset and the ACC were present (Fig. 2). These findings extend previous reports on using CAEP outcomes for confirming audibility (Chang et al., 2012; Van Dun et al., 2015) to applying CAEP measurements of ACC for verifying auditory discrimination capacities in individual infants. For NH infants, the rates of Onset responses in the present study were comparable to those previously reported for measurements conducted using the same system but with [m][g][t] as stimuli (Munro et al., 2020). This study showed that recording of ACCs with frequency-specific stimuli can provide information about auditory capacities for discrimination at different frequencies in individual infants below 6 months of age.

For infants with hearing loss, the response rates decreased as hearing loss increased. As shown in Fig. 4, the proportion of children who had Onset but not ACC responses increased with severity of hearing loss. The effect was more pronounced for the high-frequency stimulus (SRN) than for lower frequency stimuli, suggesting that even when sounds were audible with amplification for some infants, the auditory information might not be sufficient to support discrimination. For them, cochlear implants may provide more benefit than HAs. We found that on average, response rates measured at age 3–6 months were not significantly different from those measured at age 7–12 months. For infants that provided complete sets of EEG data for three stimuli at both intervals, up to 80% of HI infants who recorded ACC responses at interval 1 also had ACC responses at interval 2 (Table 6). These findings lend support to the potential of electrophysiological recording of ACCs at 3–6 months of age in hearing impaired infants, after about 6–8 weeks of HA experience.

While we have interpreted an ACC response as implying the ability to learn to discriminate between two sounds, even a level change of the same sound can generate an ACC. We have minimised the likelihood that ACCs in our experiment were caused just by a change in loudness of the stimuli, by using a loudness model to equate the loudness of all stimuli. Hearing impairment will change the relative loudness of sounds with different spectral shapes. However, the normal hearing infants had ACC responses ranging from 57% for SRN up to 100% for [uiu], so at least in their case, it was the change of spectral shape, rather than a simple change in loudness, that initiated the ACC response. We are making the assumption that it is also the change in spectral shape that generated the ACC in the case of the HI infants. This seems reasonable given that HA gain-frequency responses partially remove the effect that frequency dependent hearing loss has on the relative loudness of sounds with different spectra.

As this study was aimed to evaluate ACCs in infants who may not be able to actually discriminate between the sounds behaviorally even when typically developing, especially at interval 1, our interpretation is that the presence of an ACC indicates that acoustic differences between sounds in the stimuli are preserved in the auditory system, which gives the child the potential to learn to discriminate the sounds.

4.2. Relationship between ACC and functional performance

The second aim was to examine the relationship between CAEP outcomes and functional performance in everyday life, and a positive correlation was found. This finding is understandable, given that the presence of cortical responses and auditory function in real life are both reliant on audibility of sounds (Golding et al., 2007). While there was a significant relationship between age-corrected PEACH scores and the rates of either Onset or ACC responses in infants, the proportion of variance in PEACH scores that was explained by the combined rate of Onset and ACC responses was not high (19%), suggesting that factors other than audibility might have influenced PEACH scores (Cupples et al., 2018). The recording of ACCs to speech stimuli during infancy provides physiological evidence on auditory processing capacities that underpin development of functional performance (measured by subjective PEACH scores) that has been found to be significant predictors of children's language development (Ching et al., 2013), psychosocial outcomes and quality of life (Ching et al., 2021; Wong et al., 2018; Wong et al., 2017).

Fig. 5 shows that all the children with 0 or 1 cortical responses had low PEACH scores, and most of the children with 3 or fewer cortical responses had low PEACH scores. Consequently, we suggest that were these same stimuli to be used clinically, 3 or fewer cortical responses present out of 6 should be used to trigger consideration of getting an implant. Very low scores of 0 or 1 should strongly trigger such a consideration.

4.3. Clinical significance

This study provides evidence that supports the use of ACC as a clinical tool for the objective evaluation of auditory discrimination capacity in individual infants with hearing loss by 3–6 months of age, who have HA experience of 6–8 weeks. Clinical assessment of ACC increases knowledge about auditory capacities of individual aided infants at an early age before reliable behavioural responses can be obtained, thereby contributing to improved counselling and rehabilitation. Parents can be provided with information about their infants' sensory and neural accessibility and processing of sounds at low, mid and high frequencies to help them make intervention choices. Early identification of the limited benefits of HAs for individual infants paves the way for early cochlear implantation, leading to better outcomes (Ching et al., 2013; Ching et al., 2017; Dettman et al., 2007). Further, measurement of ACC can play an important role in a comprehensive battery of objective and subjective measures for monitoring auditory skills development in infants with hearing loss (Chang et al., 2022).

Potential applications of measuring ACCs for assessing HA efficacy may extend to children with auditory neuropathy (AN). About 10–15% of newborns identified with PCHL have auditory neuropathy (Kirkim et al., 2008; Rance, 2005), a condition characterised by the presence of pre-neural responses but an absent or severely abnormal ABR (Starr et al., 1996). Because ABR cannot provide accurate frequency specific estimates of hearing level, current management of infants with AN requires the use of behavioural observations to supplement diagnostic information until reliable behavioural thresholds can be established (AAA, 2013). It has been recommended that HA trials be implemented and those showing no HA benefit be considered for cochlear implant candidacy evaluation. As previous studies have shown that ACC could be recorded in children with AN, and the results correlated with their speech perception capacity (Dimitrijevic et al., 2011; He et al., 2015; Michalewski et al., 2005), future work will investigate the recording of ACC in infants with AN to assess HA efficacy and its relationship with functional development. Objective evaluation of HA efficacy for infants with AN would contribute to identifying those who need cochlear implants at an early age so that outcomes could be optimised (Ching et al., 2013; Myers and Nicholson, 2021).

4.4. Study limitations

Our data lend support to measuring ACC in aided HI infants by 6 months of age for evaluation of the effectiveness of amplification. There remains an uncertainty in interpreting an ACC recorded in infants as implying that behavioural discrimination will be possible. Although studies in adults have demonstrated significant associations between behavioural discrimination and electrophysiological responses (Kim, 2015; Sohier et al., 2021; Won et al., 2011), data on young children are scant. Our future work will examine the relationship between behavioural discrimination and ACC responses in young children when they can provide reliable behavioural responses.

We found that the ACC response rate was higher for [uiu] than for SRN and [szs]. This finding may relate to auditory processing capacities at different frequency regions but may also be a consequence of the order of stimulus presentation with higher noise levels for stimuli presented later. However, the latter is not consistent with a comparison of residual noise levels across stimuli that revealed no significant effect of stimulus. We reiterate the importance of controlling for residual noise levels in assessing ACCs for spectral contrasts at different frequencies.

The finding of significantly higher rates of Onset and ACC in NH infants compared to HI infants provides objective evidence on the impact of hearing loss. While this effect may be confounded by the higher proportion of NH infants with university-educated mothers and English as their native language compared to HI infants (Table 1), we think it unlikely to account for our results. Rather, the reduction in response rates as hearing level increased to severe-profound degrees is consistent with previous reports on the significant relationship between audibility and ACCs elicited with SRNs in adults (Sohier et al., 2021).

5. Conclusion

The current findings suggest that recording ACC in infants with hearing loss using a clinical tool is feasible, and reliable responses can be elicited using stimuli at low, mid and high frequencies. The objective measurement was significantly correlated with parent-reported functional outcomes in infants. Evaluation of ACC at an early age can provide parents with information about the sensory and neural accessibility and processing of sounds of infants thereby contributing to decisions about intervention choices, including cochlear implantation.

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Declaration of interest

None.

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