Value of cortical auditory-evoked potentials in audiological testing (Review)

CHRISTOS TSILIVIGKOS[1*], NIKOLAOS SAKELLARIS[2*], ELEFTHERIOS FEREKIDIS[1] and MARIOS STAVRAKAS[3,4]

[1]First Department of Otolaryngology, Hippokration General Hospital, National and Kapodistrian University of Athens, 15772 Athens, Greece; [2]Department of Otolaryngology, 'Gennimatas' General Hospital, 11527 Athens, Greece; [3]ENT Department, University Hospitals Plymouth NHS Trust, Plymouth PL6 8DH, UK; [4]Peninsula Medical School, University of Plymouth, Plymouth PL6 8BT, UK

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Abstract. Cortical auditory-evoked potentials (CAEPs) are electrophysiological responses that provide information about cortical auditory processing. The P1-N1-P2 complex is the most widely used in clinical audiology, supporting the assessment of cortical sound detection, threshold estimation in adults and older children, and the monitoring of auditory maturation. Other components, including the acoustic change complex, mismatch negativity, P300 and N400/P600, provide insight into auditory discrimination and cognitive or language-related processing, with applications at different stages of clinical development. The present narrative review discusses these responses and their use in hearing-aid evaluation, cochlear implantation, auditory neuropathy spectrum disorder and auditory training. Their clinical value and limitations are discussed, emphasizing their complementary role alongside behavioral and established electrophysiological assessments and the distinction between cortical responsiveness and functional auditory benefit.

Contents

1. Introduction
2. History of cortical auditory-evoked potentials
3. Basic concepts of electrophysiology
4. P1-N1-P2 complex and acoustic change complex
5. Mismatch negativity
6. P300 wave
7. N400/P600 waves
8. Clinical recording and interpretation of CAEPs
9. CAEPs and hearing aids
10. CAEPs and cochlear implants
11. CAEPs in auditory neuropathy spectrum disorder
12. CAEPS and auditory training
13. Conclusion

Correspondence to: Dr Christos Tsilivigkos, First Department of Otolaryngology, Hippokration General Hospital, National and Kapodistrian University of Athens, 114 Vasilissis Sofias, 15772 Athens, Greece
E-mail: tsilivig@med.uoa.gr

*Contributed equally

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1. Introduction

Auditory-evoked potentials encompass a broad range of electrophysiological responses that differ in latency, recording techniques and stimulus types (1). Based on latency, these responses are typically classified into three categories: Short-latency responses (<10 msec), middle-latency responses (~50 msec) and long-latency responses (>50 msec). It is generally accepted that these response types originate from different levels of the auditory pathway, with shorter-latency responses arising from lower auditory centers and longer-latency responses reflecting activity in subcortical and cortical regions (2).

Long-latency auditory evoked potentials is a latency-based descriptor for responses occurring beyond ~50 msec. Event-related potentials (ERPs) is a broader term for any time-locked brain response to a sensory, cognitive, or motor event, irrespective of modality. Cortical auditory-evoked potentials (CAEPs), as used in the present review, refers to the subset of auditory ERPs generated predominantly in auditory and associated cortical regions. CAEPs therefore belong to the ERP family and are long-latency by definition; however, their interpretation depends on the eliciting paradigm and the processing stage they reflect rather than on latency alone (1). When elicited using speech stimuli, they are often termed speech-evoked ERPs and are considered particularly informative, as speech represents one of the most complex and behaviorally relevant signals processed by the human auditory system (1).

CAEPs typically occur at latencies of ≥50 msec following stimulus onset and are characterized by their latency and amplitude. Latency reflects the timing of neural processing, while amplitude depends on the synchrony and spatial alignment of the activated cortical neurons and on volume conduction and recording factors, rather than simply on the number of neurons involved (3). These measures can therefore provide information about the efficiency of auditory detection and discrimination (1). Beyond basic sound detection, CAEPs provide objective insight into higher-order central auditory processes, including perception and certain aspects of cognitive auditory function (1).

For clinical purposes, CAEP components are best organized by their functional characteristics rather than by latency. Obligatory onset responses (P1-N1-P2) and the acoustic change complex (ACC) are elicited passively and index cortical detection of sound onset and of acoustic change, respectively; mismatch negativity (MMN) reflects pre-attentive deviance processing; the P300 is a task-dependent response requiring active target detection; and the N400 and P600 index higher-order, language-related processing. These groups differ in eliciting paradigm, attention requirements, functional interpretation and the level of clinical maturity, as summarized in Table I and illustrated schematically in Fig. 1. Of these, the P1-N1-P2 complex is the most widely used in clinical practice (4,5). The remaining components are associated with higher-level auditory and cognitive processing and are primarily utilized in research settings (4).

Auditory brainstem responses (ABRs) are currently well established in clinical practice as an objective method for evaluating hearing (6). By contrast, CAEPs are primarily assessed in specialized centers and still retain a largely research-oriented role. However, the widespread implementation of neonatal hearing screening programs, using otoacoustic emissions and/or automated ABRs, has enabled the much earlier identification of hearing impairment and timely intervention. This has increased the demand for objective, non-invasive and reliable methods to assess auditory system maturation in infants and young children who are unable to participate consistently in behavioral testing. In this context, CAEPs can complement brainstem-based measures by providing information about cortical-level auditory processing (7).

The aim of the present review was to summarize the key electrophysiological characteristics, clinical applications and limitations of CAEPs, with particular emphasis on their role in auditory assessment and rehabilitation. Literature was identified through searches of PubMed and Scopus for publications up to August, 2026, using the terms 'cortical auditory evoked potentials', 'P1-N1-P2', \acoustic change complex\, \mismatch negativity\, \P300\, \N400\ and 'P600', combined with terms related to audiological assessment, hearing aids (HAs), cochlear implants (CIs), auditory neuropathy spectrum disorder (ANSD) and auditory training. The reference lists of retrieved articles and relevant clinical guidelines were also screened. Priority was given to English-language original studies, systematic reviews and professional guidelines addressing CAEP physiology, recording and interpretation and clinical application in audiology. As no formal quality appraisal or meta-analysis was performed, the strength of the evidence is characterized descriptively throughout the text.

2. History of cortical auditory-evoked potentials

CAEPs were first described by Hallowell Davis in 1939, marking the earliest identification of cortical responses to auditory stimulation (5). Their systematic investigation expanded during the 1960s and early 1970s, facilitated by the development of signal-averaging techniques (5).

Historically, these responses were referred to by various terms, including slow vertex responses and auditory late responses, before CAEPs became the accepted standard terminology (5). Although their clinical application declined following the introduction of ABR, interest has resurged since the mid-1990s, driven by their capacity to evaluate higher-level auditory processing and cortical encoding of sound (1).

3. Basic concepts of electrophysiology

Neurons ascending from the cochlea to higher auditory nuclei exhibit a spontaneous firing rate even in the absence of external stimulation. When an auditory or electrical stimulus is presented, the intracellular membrane potential must reach a specific threshold before an action potential is generated (8).

In addition, each neuron has a characteristic electrical resistance (R) and behaves as a capacitor, consisting of two conductive compartments, the intracellular and extracellular spaces, separated by a dielectric medium, the cell membrane. This configuration creates an electrical potential difference (voltage) across the membrane (3). The process reflects the summation of excitatory synaptic inputs leading to membrane depolarization; once threshold is reached, voltage-gated sodium channels open, triggering an all-or-none action potential that propagates along the auditory pathway (9).

Scalp-recorded potentials, however, arise mainly from synaptic transmembrane currents rather than from action potentials: Fast sodium spikes are brief (<2 msec) and rarely synchronous across neighboring neurons; thus, their contribution to the scalp electroencephalography (EEG) is minimal (3). Synaptic currents in pyramidal neurons, whose apical dendrites lie parallel to one another, form current dipoles that summate when the neurons are spatially aligned and synchronously active (3). The return currents of these dipoles spread through the head tissues, white matter, cerebrospinal fluid, meninges, skull and scalp, which exhibit distinct electrical conductivities. Consequently, in addition to intracellular ionic currents, extracellular ohmic currents are generated simultaneously. This phenomenon, known as volume conduction, underlies the potentials measured at the scalp. These signals can be recorded using either electrical recordings in EEG or magnetic field recordings in magnetoencephalography (MEG) (3,10). Scalp-recorded CAEPs provide an indirect, composite measure of cortical population activity, with their amplitude and morphology influenced by factors such as neural synchrony, source orientation and geometry, individual anatomy, and recording and signal-processing methods (3,5).

EEG is most widely used in clinical practice due to its practicality and cost-effectiveness. However, magnetic signals are much less dependent on the conductivity of the extracellular space than MEG, and capacitive properties of the skin and scalp muscles distort the electrical but not the magnetic signal (3). Furthermore, EEG signals reflect activity from both

Table I. Main characteristics, functional interpretation, clinical applications and limitations of cortical auditory-evoked potentials.

Component	Typical paradigm	Approximate latency	Attention/task requirements	Principal functional interpretation (Refs.)	Clinical application and maturity (Refs.)	Major limitations (Refs.)
P1-N1-P2	Repeated clicks, tones, or brief speech sounds.	Adults: P1 ~50 msec; N1 ~100 msec; P2 ~200 msec. P1 is later in infants.	No active response; generally awake and alert.	Sound-onset detection; P1 latency reflects auditory cortical maturation (1,5,7).	Relatively established adjunct: Adult/older-child threshold estimation. Selected adjunct: Amplified-sound detection (7). Emerging: Pediatric CI/ANSD monitoring and CI programming (5,35,36,39).	Age, recording conditions, and device processing affect responses. Average threshold agreement does not ensure individual accuracy; response presence does not establish speech understanding (5,7,35,39).
ACC	Acoustic change within an ongoing sound.	Time-locked to the change; age- and stimulus-dependent.	No active discrimination task.	Cortical detection of acoustic changes (1,27).	Emerging adjunct assessing acoustic fordiscrimination, including in CI users (1,27).	Reliability and behavioral agreement depend on protocol and population. Normative data are needed; contrast detection does not establish speech recognition (1,27).
MMN	Infrequent deviants among repeated standard sounds.	Usually ~150-250 msec.	No active discrimination task.	Pre-attentive processing of auditory deviations (1,17).	Mainly research: auditory discrimination and training-related plasticity (1,18).	Detectability and test-retest reliability vary. Group findings do not establish individual diagnostic or predictive accuracy (1,17,18).
P300	Oddball task with infrequent targets.	Typically ~300 ms in young adults performing simple tasks.	Active target detection.	Task-dependent target detection and cognitive processing (19).	Investigation of auditory discrimination and cognition (19).	Influenced by target probability, task difficulty, engagement, age, and cognitive status (19).
N400/ P600	Semantic or morphosyntactic manipulations; also musical paradigms.	N400: ~250-550 msec. P600: ~500-1,000 msec.	Task-dependent.	N400: Meaning-related processing. P600: Later integration/ reanalysis; functions overlap (22-25).	Mainly research: Language and music processing beyond sound detection (20-25).	Language, context, modality, and task effects; no established individual audiological diagnostic cutoffs or predictive accuracy in the reviewed studies (22,25).

ACC, acoustic change complex; ANSD, auditory neuropathy spectrum disorder; CI, cochlear implant; MMN, mismatch negativity.

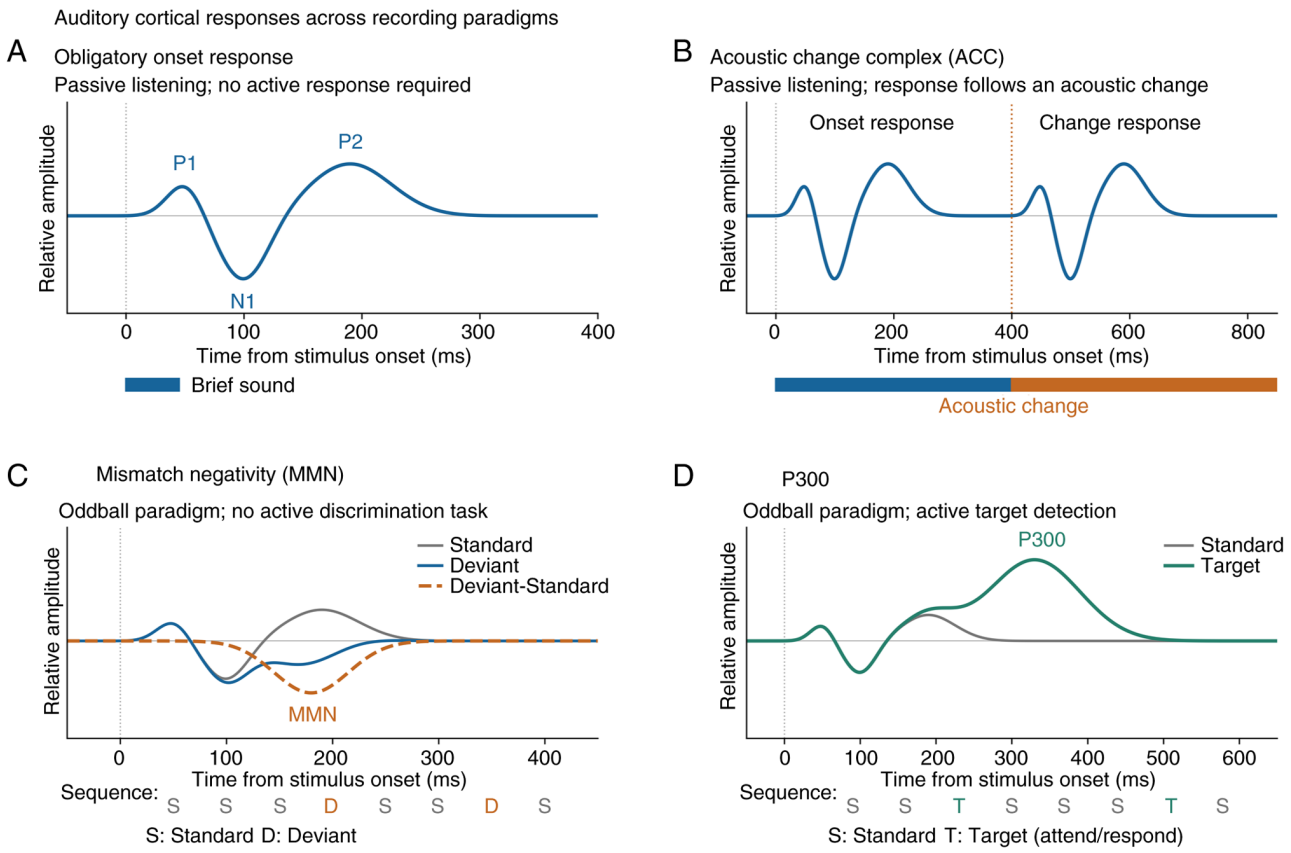


Figure 1. Schematic illustration of cortical auditory-evoked potentials across recording paradigms. (A) P1-N1-P2 complex, (B) acoustic change complex (ACC), (C) mismatch negativity (MMN), (D) P300 wave. Of note, the figure illustrates schematic waveforms, not recorded data. Positive voltage plotted upward; timing and amplitudes are illustrative. Stimulus sequences are symbolic and are not aligned to the response time axes.

sulcal and gyral sources, whereas MEG is primarily sensitive to tangential currents arising from sulcal activity. Consequently, MEG provides greater spatial specificity for tangential cortical currents, while EEG reflects a broader distribution of cortical electrical activity (11).

4. P1-N1-P2 complex and acoustic change complex

The P1-N1-P2 complex is typically elicited by brief auditory stimuli, such as clicks, tones, or short speech sounds. As these responses are embedded within ongoing EEG activity, repeated stimulus presentation is required to obtain time-locked responses, which can then be averaged to enhance the SNR and separate the evoked activity from background EEG (12).

Stimulus repetition rate and the number of accepted trials depend on the age of the patient and the recording purpose. For clinical threshold estimation, the number of trials should be guided by response amplitude and residual noise, with smaller near-threshold responses generally requiring more averaging (5). Within this complex, the N1 (or N100) component is a negative peak occurring at ~100 msec post-stimulus and is often used as a reference point, situated between the two positive peaks P1 (~50 msec) and P2 (~200 msec). The majority of the literature focuses primarily on the N1 and P2 components (12).

It is currently well established that P1 is a distinct component, separate from the Pb response of middle latency auditory potentials. P1 is generated within a distributed cortical network, including the primary auditory cortex (Heschl's gyrus), hippocampus, planum temporale, lateral temporal regions, and possibly subcortical structures (1). In adults, P1 is typically of low amplitude, whereas in children it is a prominent peak, followed by a relatively slow N2 component (1). Selected auditory event-related potential components and their eliciting paradigms are illustrated schematically in Fig. 1.

Among CAEP components, P1 latency has been identified as a particularly useful electrophysiological marker of central auditory pathway maturation in both normal-hearing children and pediatric CI users. It is considered to reflect cumulative synaptic transmission delays and neural conduction time from the auditory periphery to the primary auditory cortex (7). P1 latency decreases systematically with maturation, from ~300 msec in newborns and infants to ~100 msec by the age of 2 years, followed by a more gradual reduction toward adult values. This developmental trajectory, documented largely at group level, supports its use as an objective marker of auditory system maturation in the pediatric population, although normative latency ranges vary across studies and recording protocols (7,13).

N1 and P2 are the dominant components of the waveform in adults. With high density recording, the following sub-components of N1 can be distinguished: N1a at temporal electrodes (75 msec), N1b at vertex electrodes (100 msec) and N1c at temporal, fronto-polar and lateral central electrodes (130 msec). The majority of studies referring to N1, actually refer to N1b. The faster the stimulus rate is, the smaller the

N1 amplitude is. P2 also arises from multiple areas: Primary and secondary auditory cortex, mesencephalic reticular formation. It is of importance to note that N1 and P2 do not arise from the same mechanism (1,14). A split P2 morphology may occasionally be observed, suggesting that P2 may reflect more than one stage of higher-order auditory processing rather than a single uniform cortical event (15,16).

The P1-N1-P2 complex can be reliably recorded in individual listeners, supporting its use in objective auditory assessment. Interpretation should account for age, stimulus parameters, and alertness, which influence response morphology, amplitude and latency (1,5). It is characterized as an onset response or a change detector, as it is evoked by onset, changes in the envelope and offset of sound. It is also known as an obligatory response as it is present following cortical stimulation in the conditions and is a passive recording, which means that the patient must be awake and alert but does not need to respond actively to stimuli. P1-N1-P2 complexes of onset, change and offset share the same characteristics, even when elicited by different stimuli. The complex of offset is generally of lower amplitude than the other two (1).

The P1-N1-P2 response provides a useful objective estimate of hearing thresholds in awake adults and older children, particularly when reliable behavioral responses cannot be obtained (5). Threshold estimation is based on identifying the lowest stimulus level at which a cortical response is detected. CAEP thresholds typically exceed behavioral thresholds by an average of ~5-10 dB, although individual differences vary with the recording and analysis methods (5). This represents a relatively established adjunctive application; in infants and young children, suprathreshold CAEPs are more appropriately used to assess cortical sound detection than to predict hearing thresholds (5). However, as the P1-N1-P2 complex is highly dependent on attention, alertness and sleep state, it cannot be reliably recorded in infants and children during sleep. By contrast, in adults who are unable or unwilling to provide behavioral responses, it can be measured either alone or in combination with ABR for the assessment of hearing thresholds, and it reflects neural activity beyond the level of the brainstem (1).

The ACC reflects the cortical detection of dynamic changes within an ongoing auditory signal, particularly variations in frequency or intensity during sustained stimulation (1,14). Unlike the classical P1-N1-P2 complex, which is primarily an onset response to brief stimuli and appears as a single waveform, the ACC is elicited by changes occurring within the stimulus itself and therefore provides information on neural processing beyond stimulus onset. In speech, where the acoustic envelope is continuously modulated, multiple ACC responses may be elicited, most commonly at consonant-vowel transitions (14). This supports the concept that the ACC reflects the ability of the brain to detect and encode acoustically relevant changes that are critical for speech perception and complex auditory discrimination (14).

The ACC provides an objective measure of cortical responses to acoustic contrasts, with reported agreement between electrophysiological and behavioral discrimination thresholds for specific stimulus changes. It can be recorded without an active task and good test-retest reliability has been reported in normal-hearing adults (1). These findings support its potential as a complementary measure of auditory discrimination. Individual interpretation nevertheless requires the consideration of stimulus characteristics and appropriate normative data, while cortical detection of an acoustic contrast should be distinguished from successful speech recognition (1).

5. Mismatch negativity

In the MMN paradigm, auditory discrimination is assessed using an oddball design in which frequently presented standard stimuli are interspersed with infrequent deviant stimuli (1). Deviations may involve changes in frequency, duration, intensity, spatial location, or phonemic content. The MMN is not obtained directly from single-trial responses but is derived from a difference waveform, calculated by subtracting the response to the standard stimulus from that to the deviant stimulus. It typically emerges following the N1 component, within a latency range of approximately 150-250 msec. The MMN can be elicited without active attention to the auditory stimuli, allowing for the assessment of pre-attentive deviance processing without an explicit behavioral task (1,17).

Neurophysiologically, the MMN is generated primarily in the primary and secondary auditory cortices, with additional contributions from frontal cortical regions. It is widely interpreted as an index of pre-attentive auditory and speech discrimination, arising when an infrequent deviant violates the sensory memory trace established by the repetitive standard stimuli. Importantly, the MMN is typically elicited only when the acoustic difference is perceptually detectable, linking the response to functional discrimination rather than mere physical stimulus variation (1,17).

The MMN provides a valuable means of investigating auditory discrimination without requiring an active response. Its reliability, however, depends on the paradigm and population: good test-retest reliability has been reported in psychiatric research, whereas speech-evoked MMN may be inconsistently detected in individual listeners, particularly children (1,17). The need for numerous deviant presentations also increases recording time (1). These findings support its value in research, while highlighting the need for application-specific validation before group-level effects can be used for individual audiological assessment.

Nevertheless, the MMN remains highly valuable in research contexts due to its sensitivity to experience-dependent plasticity in auditory processing. Kraus *et al* (18) demonstrated that auditory training can modify electrophysiological responses of the central auditory system to subtle speech contrasts. Although MMN was present in 10 of 13 adult participants before training, it was observed in all participants after training, indicating that auditory experience can induce measurable changes in cortical responses to speech contrasts (18). This demonstrates sensitivity to training-related auditory plasticity, although findings from this small normal-hearing adult sample do not establish the accuracy of MMN for predicting rehabilitation benefit in individual patients (18).

6. P300 wave

The P300 waveform (P3) is an active cortical auditory-evoked potential elicited using oddball paradigms. In contrast to

passive responses, such as MMN, participants are required to perform a task or provide a response when deviant stimuli are detected (19). The stimulus characteristics are similar to those used in MMN paradigms. The P300 appears as a positive peak occurring ~200-300 msec following stimulus onset and is considered to be generated across a distributed network involving the auditory cortex, centro-parietal cortex, hippocampus and frontal cortex. P300 latency and amplitude are modulated by task difficulty: easier stimulus discrimination is associated with larger amplitudes and shorter latencies (19).

In this manner, the P300 is considered to reflect auditory discrimination, as well as higher-order cognitive processes, such as attention and stimulus evaluation. However, several limitations restrict its clinical utility. There is a lack of robust normative data and considerable inter-individual variability in responses (19). The P300 is also influenced by factors, such as alcohol consumption, aging, dementia and schizophrenia, all of which may alter waveform characteristics even when basic auditory discrimination remains intact. Furthermore, as the paradigm requires active participation and task performance, its added diagnostic value over other discrimination measures is limited. For these reasons, the P300 is primarily used as a research tool rather than a routine clinical assessment method (19).

7. N400/P600 waves

These CAEPs are widely used in speech processing research. The N400 component is associated with the encoding of semantic information and is characterized as a negative peak occurring between 250-550 msec, with a maximum ~400 msec (20-22). More specifically, semantic incongruity within a sentence leads to an increase in N400 amplitude (20,21,23). Conversely, greater semantic congruency is associated with a reduction in N400 amplitude, reflecting facilitated semantic integration (23).

The P600 is a positive-going component occurring approximately 500-1,000 msec post-stimulus, with a typical peak around 600 msec. Its amplitude increases in response to morpho-syntactic violations within sentences (24). However, more recent CAEP research suggests that the association between N400 and P600 is more complex than a simple dissociation between semantic and syntactic processing (25). Although semantic incongruities classically elicit an N400 effect, certain semantically implausible or anomalous sentences may also evoke a biphasic N400-P600 response. This pattern indicates that lexical-semantic retrieval and integration into an evolving sentence representation may involve partially distinct but overlapping neural processes. The variability in P600 occurrence has been linked to factors, such as task demands, depth of semantic processing and temporal overlap between ERP components (25).

These CAEP components are also investigated in music cognition research. The N400 amplitude increases when participants are presented with incongruent pairings of musical context and words. In addition, the P600 amplitude is enhanced in response to harmonic violations, such as out-of-tune chords, reflecting the detection of structural irregularities in musical sequences (20,21). N400 and P600 responses provide valuable information about language processing beyond sound detection. The N400 has also enabled the investigation of semantic processing in populations with limited ability to complete conventional cognitive tasks (22). Interpretation depends on language proficiency, stimulus context, and task demands (22,25). The studies discussed herein support their value as research measures, but do not establish standardized diagnostic cut-offs or predictive accuracy for individual audiological assessment (20-25). The main characteristics and clinical roles of the cortical auditory responses discussed above are summarized in Table I.

8. Clinical recording and interpretation of CAEPs

A critical aspect of the clinical application of CAEPs is the standardization of recording and interpretation procedures. Reliable responses require appropriate electrode placement, typically in a vertex-to-mastoid montage, with low and balanced electrode impedances. Recording parameters should be optimized for cortical activity, including appropriate filtering of low-frequency activity and relatively long inter-stimulus intervals to avoid neural adaptation. Test conditions must minimize electrical and physiological artefacts, while ensuring patient alertness, as drowsiness or inattention can significantly alter waveform morphology (5). Stimulus characteristics, presentation level and rate, calibration, electrode reference, filter settings, artefact-rejection criteria, and the number of accepted trials should be documented to support interpretation and comparison across recordings (5).

Interpretation should not rely on a single averaged trace, but on reproducible responses across repeated recordings, with the identification of characteristic components (e.g., P1-N1-P2) demonstrating expected latency and amplitude changes with stimulus intensity (5). Response identification should consider waveform morphology, repeatability and signal-to-noise ratio, using explicit visual or statistical detection criteria. An absent response is interpretable only when residual noise is sufficiently low to permit detection of a small response (5). The CAEP threshold is typically defined as the lowest stimulus level at which a replicable response is present, with the absence of response at lower intensities. However, electrophysiological thresholds may differ from behavioral thresholds by several decibels. Suboptimal recording conditions and reduced alertness should also be considered before attributing an absent response to impaired cortical sound detection (5).

CAEPs add information about cortical auditory processing to the established audiological test battery. Otoacoustic emissions assess cochlear outer hair cell function, while ABR evaluates neural responses through the brainstem and supports objective threshold estimation (6). Auditory steady-state response (ASSR) provides a further means of estimating frequency-specific hearing thresholds. CAEPs extend this assessment by demonstrating cortical responses to sound, including amplified stimuli, and by characterizing acoustic-change processing and auditory maturation (1,5). This information is particularly useful when behavioral responses are limited or inconsistent. Behavioral audiometry and speech-perception testing remain essential, when feasible, for determining hearing sensitivity and functional performance; cortical responses provide complementary physiological information rather than equivalent measures of speech understanding (1,5,6).

CAEPs can provide complementary information for auditory threshold estimation, the assessment of acoustic discrimination, and the evaluation of cortical responses to HAs, CIs and auditory training (26-30). Table II provides a comparison of the principal features and complementary roles of CAEPs (5), ABR (31), ASSR (32) and behavioral pure-tone audiometry (33) in hearing assessment.

In contemporary pediatric audiology, the role of CAEPs has expanded beyond detection alone, as they can objectively verify whether amplified speech signals are effectively reaching and activating cortical auditory areas, thereby serving as a complement to behavioral measures (34). Furthermore, the longitudinal assessment of P1 latency may serve as an adjunctive marker of cortical auditory maturation following cochlear implantation, particularly during early developmental stages when reliable behavioral or language-based testing is not yet feasible (7).

9. CAEPs and hearing aids

There are several approaches to recording CAEPs in individuals using HAs, with sound-field stimulation being the most commonly used method in both clinical and research settings. HAs primarily increase the intensity, and therefore the audibility, of incoming sounds; however, improved audibility does not necessarily translate into proportional improvements in auditory perception (35). In addition, signal processing within the device alters both the temporal envelope and spectral properties of the sound, thereby modifying the acoustic input delivered to the auditory system (35).

These factors may partly explain why increases in HA gain are not consistently associated with corresponding increases in CAEP amplitude or systematic reductions in latency. Variability in CAEP responses is further influenced by device-related factors, such as HA type and programming settings, as well as listener-related characteristics. For example, individuals with presbycusis often present with combined peripheral and central auditory deficits, including impaired temporal processing, which may limit cortical responses despite adequate amplification (35).

Although aided CAEPs have been associated with aided behavioral thresholds (36), this association does not establish accurate threshold prediction in individual patients. A systematic review found predominantly fair- or poor-quality studies and highlighted gaps in age-specific normative data and standardized assessment procedures (37). Aided CAEPs may therefore provide complementary evidence of cortical detection of amplified speech, particularly when behavioral testing is limited. However, responses depend on hearing-aid processing and listener-related factors (35), and their presence does not establish speech understanding or functional benefit. Individual interpretation requires attention to response reproducibility and should be integrated with hearing-aid verification, behavioral audiometry and age-appropriate speech-perception assessment.

10. CAEPs and cochlear implants

CAEPs provide a valuable means of studying cortical auditory processing and have been widely applied in the assessment of auditory function in CI users (27). In children with severe hearing loss, the development of the P1 component is often delayed and may not fully reach the maturity observed in normal-hearing peers, even after implantation. The electrically evoked ACC has been proposed as an objective indicator of sensitivity to changes within ongoing auditory stimuli in CI users, with cortical responses influenced by stimulation parameters, particularly the spatial separation of activated electrodes (27).

In CI users, auditory responses are shaped by multiple device- and stimulation-related factors (38). Sound is captured by a microphone, processed into frequency-specific channels, and delivered via an intracochlear electrode array that encodes intensity and frequency information. Consequently, stimulus characteristics (type and intensity), the number of active channels, and electrode configuration all influence CAEP morphology. CI programming parameters therefore have a substantial impact on recorded cortical responses (27).

CAEPs in both HA and CI users reflect a combination of neural processing and device characteristics, making it challenging to fully separate biological from technological influences (27). However, this does not diminish their clinical value; rather, it underscores the need for careful interpretation. In CI users, CAEPs primarily reflect the interaction between electrically mediated auditory input and auditory experience, rather than purely normative cortical maturation (29,30). Accordingly, changes in P1 latency should be interpreted as markers of functional cortical reorganization rather than complete physiological normalization, particularly when auditory input is introduced during a sensitive developmental period (30).

When interpreting CAEPs in pediatric CI users, chronological age alone is insufficient. Hearing age, defined as the duration of effective auditory experience following implantation, is a critical determinant of cortical maturation (4). Outcomes depend not only on time since activation, but also on whether implantation occurred within the sensitive period and was followed by consistent auditory stimulation and spoken-language exposure. Early implantation alone may not yield optimal outcomes if auditory input is inconsistent or limited (15,16).

Cochlear implantation induces measurable changes in central auditory pathways, most notably a rapid reduction in P1 latency, particularly when activation occurs before approximately 3.5 years of age (29). This reflects the high neuroplasticity of the developing auditory system. Children implanted within this sensitive period often show near-normal P1 latencies within 6-8 months of device use, whereas later implantation is associated with persistently prolonged latencies and atypical CAEP morphology, consistent with reduced cortical plasticity (29,30). Prolonged auditory deprivation beyond ~7 years may result in persistent abnormalities in cortical responses (29). The P1 component has therefore been proposed as a promising adjunctive marker for monitoring cortical auditory maturation following early cochlear implantation (29).

As the development of central auditory pathways is closely linked to auditory experience, CAEPs, reflecting thalamocortical and cortical activity, provide useful information about cortical auditory maturation following implantation (13).

Table II. Comparison of CAEPs, ABR, ASSR and behavioral pure-tone audiometry in hearing assessment.

Assessment	Typical stimuli	Principal level assessed	Attention/alertness requirements	Main clinical utility	Threshold determination
CAEPs: Obligatory onset responses	Tone bursts or brief speech sounds; presentation through earphones, bone conduction, or sound field.	Cortical auditory responses to sound.	No active behavioral response required; testing is generally performed awake and alert.	Adjunctive threshold estimation in adults and older children; assessment of cortical detection of amplified sounds when behavioral testing is limited.	Lowest level eliciting a reproducible cortical response, with response absence demonstrated at a lower level under adequate recording conditions. Electrophysiological-behavioral differences must be considered.
ABR	Clicks, tone pips, or chirps; frequency-specific stimuli are preferred for frequency-specific threshold estimation.	Auditory nerve and brainstem pathways.	No active response required; natural sleep or a very relaxed state facilitates recording. Sedation may be needed in selected patients.	Objective threshold estimation when behavioral responses are unreliable; assessment of neural response morphology and timing.	Lowest level producing a clear, reproducible response, typically identified through wave V, with an absent response 5-10 dB below. Appropriate correction values convert electrophysiological thresholds to estimated behavioral hearing levels.
ASSR	Amplitude- and/or frequency-modulated tones, or repeating narrow-band chirps; several frequencies may be tested simultaneously.	Generator contributions depend on modulation rate: approximately 90-Hz responses are predominantly brainstem-related; approximately 40-Hz responses include contributions associated with middle-latency activity.	No active response required. Approximately 90-Hz testing is suitable during sleep; approximately 40-Hz testing is appropriate for awake older children and adults.	Objective, frequency-specific threshold estimation, including simultaneous testing at multiple frequencies and in both ears. Complements ABR.	Lowest level meeting statistical response-detection criteria, supported by testing at adjacent levels and adequate residual-noise control. System- and stimulus-appropriate corrections are used to estimate behavioral hearing levels.
Behavioral pure-tone audiometry	Frequency-specific tones delivered through air- or bone-conduction transducers.	Behavioral sound detection involving the auditory pathway as a whole; does not isolate a single neural generator.	Awake, attentive participation and a reliable task response are required; the task is adapted to developmental ability.	Direct measurement of hearing sensitivity; air- and bone-conduction findings help characterize hearing loss.	Lowest level at which reliable behavioral detection is obtained at each frequency using a standardized threshold-seeking procedure.

CAEPs, cortical auditory-evoked potentials; ABR, auditory brainstem response; ASSR, auditory steady-state response.

Reductions in P1 latency appear to parallel improvements in auditory perception and spoken language development, although P1 itself reflects cortical maturation rather than language ability directly (13,39). In children with delayed language development, CAEPs may provide complementary information when considering insufficient auditory stimulation

or broader developmental disorders as possible contributing factors, alongside language testing and developmental assessment (7). Beyond assessing maturation, CAEPs may support CI programming, particularly in patients unable to provide reliable behavioral feedback (40). Determining the electrical dynamic range across electrodes is essential but challenging in infants and young children. While objective measures, such as electrically evoked compound action potentials assess peripheral neural responses, they correlate only weakly with behavioral thresholds (40). In contrast, CAEPs reflect cortical processing of clinically relevant stimuli. Cortical thresholds derived from amplitude growth functions, particularly using global field power, have shown strong agreement with behavioral thresholds in adults, suggesting potential utility in objective CI fitting (40). Clinical studies in adults with bilateral hearing loss or single-sided deafness have also reported improved speech recognition in quiet or noise following CAEP-guided map adjustments in subgroups who achieved responses to all tested speech tokens. These findings support the potential of CAEPs as an adjunct to CI fitting, although the absence of randomized comparisons with conventional remapping and selective post-adjustment speech testing limit conclusions about their added benefit (41,42). Clinically, absent or delayed cortical responses may prompt the reassessment of mapping parameters or intensification of auditory rehabilitation (31).

A major technical challenge in CI-based CAEP recording is electrical artifact generated by the implant, which is time-locked to the stimulus and may overlap with early cortical components such as P1 (7). This artifact can obscure true neural responses and necessitates dedicated artifact-reduction strategies. The issue is often more pronounced in bilateral CI users, where standard electrode configurations are less effective in minimizing interference (43).

Recent developments have enabled CAEP recording directly through CI electrodes using backward telemetry. An initial feasibility study recorded responses to acoustic stimulation of the contralateral, non-implanted ear, demonstrating correspondence with simultaneously recorded scalp CAEPs (16). A subsequent study in bilateral CI users recorded electrically evoked cortical responses through the contralateral implant and reported associations with auditory and speech performance (15). These findings support the potential of implant-based cortical assessment, although its role in routine clinical management requires further validation. Speech-evoked CAEPs further enhance clinical relevance by providing frequency-specific insights into cortical access to speech cues. Stimuli, such as /m/, /g/ and /t/ represent low-, mid- and high-frequency information, respectively, allowing for the evaluation of spectral access across the speech range (34). Notably, the maturation of cortical responses may vary across frequencies, reflecting differences in audibility, electrode placement, or programming parameters. This highlights the importance of stimulus selection in interpreting CAEP results (34).

Despite technological advances, a number of CI users continue to experience difficulty understanding speech in noisy environments, even when performance in quiet conditions is adequate. This underscores the gap between device performance and real-world auditory function (44).

Finally, CAEP findings in CI users must be interpreted within the broader clinical context. Normal cortical responses do not guarantee favorable speech or language outcomes, particularly in children with additional neurodevelopmental conditions such as autism spectrum disorder or global developmental delay (15). Similarly, in auditory neuropathy spectrum disorder, cortical responses may appear relatively normal despite persistent deficits in neural synchrony and variable behavioral outcomes (15).

Overall, CAEPs provide complementary information on cortical auditory maturation following implantation; however, variable latency values, inconsistent morphological criteria, and associations with language performance that differ across assessments limit individual prognostic interpretation (7,13). In a previous study on 22 pediatric CI recipients, CAEP latencies exhibited lower between-subject variability than amplitudes, and acoustically evoked P1 latency was less variable than electrically evoked P1 latency (45). These findings help characterize variability across recording approaches, although test-retest reliability was not assessed (45). CAEP-based programming remains an emerging adjunctive application, supported by promising adult threshold estimates and reported speech-perception gains after map adjustments; controlled comparisons and pediatric validation are still required (40,42). Implant-based recordings have demonstrated technical feasibility and associations with speech performance, including additional explanatory value beyond age at implantation, but these findings do not yet establish externally validated individual prediction or improved clinical outcomes (15,16). CAEPs should therefore complement behavioral mapping, speech-perception testing and language assessment.

11. CAEPs in auditory neuropathy spectrum disorder

In ANSD, CAEPs can provide clinically valuable information, particularly when ABRs are absent or severely abnormal due to neural dys-synchrony, while slower cortical responses remain detectable (46,47). The P1 component, in particular, has been associated with auditory cortical maturation and may help reveal differences in central auditory development among children with ANSD that are not captured by peripheral measures alone. More robust or age-appropriate P1 responses have also been linked to more favorable speech and language outcomes (46,47).

Prospective evidence supports the potential of CAEPs for monitoring cortical maturation in children with ANSD following cochlear implantation: Over 2 years, P1 responses improved, and shorter latencies were associated with better speech intelligibility ratings (46). These findings support a complementary role in follow-up, although the small, early-implanted cohort limits generalizability and do not establish predictive accuracy for individual patients. CAEPs can provide evidence of cortical responsiveness when ABRs are absent or abnormal; however, their presence alone does not establish normal speech perception (47). Results should therefore be interpreted alongside behavioral audiometry, speech-perception testing, and developmental assessment.

12. CAEPs and auditory training

Auditory rehabilitation incorporates a range of training exercises, typically based on repeated exposure to sounds, with

the aim of improving auditory perception. Repeated auditory exposure can induce lasting changes in cortical responses, including increased P2 amplitude, even without formal training or measurable perceptual improvement (28). CAEPs can provide a useful tool for linking such neurophysiological changes to improvements in sound discrimination, while also helping to identify situations in which electrophysiological and behavioral outcomes do not align (28).

Although auditory training can enhance specific discrimination abilities, these improvements are often task-specific and do not consistently generalize to broader functional outcomes, such as speech perception in noise. Even when benefits in noisy environments are observed, they are typically modest and restricted to favorable listening conditions or SNRs (44).

Speech perception in noise relies not only on peripheral auditory encoding, but also on higher-order cognitive processes, including attention, memory and linguistic integration. These factors may limit the effectiveness of purely auditory-based training approaches. The interaction between bottom-up auditory processing and top-down cognitive mechanisms remains incompletely understood and likely contributes to variability in outcomes among CI users and across training programs (44).

Effective speech perception in noise also depends on the accurate spectrotemporal encoding of acoustic signals. In CI users, limitations in spectral resolution represent a major constraint compared with normal-hearing individuals. Consequently, reduced speech perception performance may reflect not only technological limitations of the implant but also the capacity of the auditory nervous system to process and interpret incoming signals, capacities that may be shaped, at least in part, by experience and training (44).

CAEPs provide complementary information about neural adaptation associated with auditory training. In a previous study, in 10 adult CI users, short-term training was associated with improved speech recognition in noise and increased N1-P2 amplitude in one recording condition, although electrophysiological and behavioral changes were not associated (44). Although three pretraining assessments strengthened the baseline comparison, the small sample size and the absence of an untrained control group limit the attribution of these changes specifically to training, particularly as stimulus exposure alone can modify P2 responses (28,44). These findings support CAEPs as research tools for investigating auditory plasticity; their use to quantify individual rehabilitation benefit remains investigational and should be evaluated alongside behavioral outcomes. A recent study on adult CI users undergoing a 10-week structured aural rehabilitation program reported improvements in speech recognition without significant changes in electrically evoked CAEP latencies or amplitudes (48). Although the study included a control group, allocation was not randomized. These findings suggest that functional gains may occur without detectable changes in the recorded cortical responses, highlighting the importance of assessing rehabilitation outcomes using complementary behavioral and electrophysiological measures (48).

At present, there are no standardized guidelines regarding the optimal type, duration, or intensity of auditory training and maintaining patient adherence remains a significant challenge in clinical practice (44).

13. Conclusion

CAEPs provide valuable information about cortical auditory processing that complements peripheral and brainstem assessments. Their most established adjunctive applications include threshold estimation in adults and older children, while the assessment of cortical responses to amplified sounds can support evaluation when behavioral findings are limited or inconsistent. P1 latency provides an adjunctive marker of auditory cortical maturation, including in children with CI or auditory neuropathy spectrum disorder; however, it does not independently establish functional normalization or predict individual speech and language outcomes. Emerging applications include acoustic-change assessment and CAEP-guided CI programming, with adult studies reporting speech-perception gains after map adjustments. Cognitive and language-related responses and electrophysiological monitoring of auditory training remain predominantly research-oriented in audiology. Clinical interpretation requires the consideration of recording conditions, developmental factors, and device processing, alongside behavioral and speech-perception findings. Further research is required to prioritize standardized protocols, test-retest reliability and evidence that CAEP-informed decisions improve patient outcomes.

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Authors' contributions

CT Conceptualized the study. CT and MS were involved in the study methodology (literature search and study collection). CT and NS were involved in the writing and preparation of the original draft of the manuscript. EF and MS were involved in the writing, reviewing and editing of the manuscript. EF and MS supervised the study. All authors have read and approved the final version of the manuscript. Data authentication is not applicable.

Ethics approval and consent to participate

Not applicable.

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Not applicable.

Competing interests

The authors declare that they have no competing interests.

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