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Development of cortical auditory processing and its association with speech understanding from childhood to adulthood

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The maturation of the auditory system is critical for the development of speech perception from childhood through early adulthood. However, the developmental trajectories and behavioral significance of cortical responses to speech sounds, particularly in relation to frequency specificity, remain poorly understood. Here, we presented low-frequency (/m/) and high-frequency (/s/) speech sounds to 70 typically developing individuals aged 5–24 years and recorded early cortical responses (P1 and N1) using electroencephalography. We also examined associations between these neural responses and speech understanding in quiet and in the presence of speech interferers. The developmental trajectories of P1 and N1 revealed distinct age- and stimulus-dependent patterns, including both linear and non-linear changes across development. These findings delineate frequency-specific maturational profiles within the cortical auditory system and identify potential neurophysiological markers of speech perception, providing a normative benchmark for assessing atypical auditory development.

Keywords Auditory maturation, Speech cortical processing, Cortical auditory evoked potentials, Speech understanding, EEG

The maturation of the human auditory system is a long and complex process, undergoing significant developmental changes from the embryonic period to early adulthood[1]. The peripheral auditory system is relatively mature in infancy, but the central auditory system develops more gradually. Brainstem auditory pathways show considerable maturation by early childhood, although brainstem auditory functions may undergo further refinement over time[2,3]. Cortical auditory areas show more protracted development and continue to mature well into late adolescence[2,4,5]. During the postnatal developmental period, auditory brain regions undergo structural and functional changes that are shaped by both inherent (genetic) and environmental (sensory) factors[6–8].

The functional developmental trajectory of the central auditory system can be observed through neurophysiological responses to auditory stimuli recorded using electroencephalography (EEG) techniques[4,9]. Specifically, in awake, neurotypical individuals with normal hearing, passive listening to auditory stimuli elicits obligatory cortical auditory evoked potentials (CAEPs)[10,11]. These CAEPs result from the summation of temporally overlapping electrical activity at multiple neural sources and, in adults, appear as a sequence of positive-negative-positive-negative deflections ~ 50 to 300 ms post-stimulus onset, commonly referred to as the P1-N1-P2-N2 complex[12,13]. This multiphasic complex is prominent at the vertex or Cz (the center of the scalp) and Fz (midline frontal) electrodes, but its constituent peaks represent contributions from multiple distributed neural sources, and the weight of these contributions depends on the position of the recording electrode[12,14]. P1 is linked mainly to activity in the lateral portion of Heschl's gyrus, i.e., secondary auditory cortex, N1 to primary and secondary auditory cortices, and P2 to a broader network including auditory cortex, association cortices, and the reticular activating system[12,14–18]. Acoustic features of stimuli are known to influence the amplitudes and latencies of CAEP peaks. For example, differences in stimulus parameters such as frequency, level, inter-stimulus interval, rise time, spectro-temporal complexity, and speech vs. non-speech stimuli, all influence CAEP characteristics[19–21]. The latency and amplitude of CAEP peaks are also highly dependent upon electrode location, the integrity of the auditory pathway, and the organization of cortical auditory areas, including the primary and secondary auditory cortices[12,17,22].

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CAEPs, particularly the P1 and N1 responses, undergo age-related changes from infancy to adulthood that serve as indices of auditory cortical maturation[2,12,13,23–25]. CAEP responses are present in newborns and young infants; however, the morphology, latency, amplitude, and scalp distribution of CAEPs during development differ greatly from adult responses[21,25,26]. Several maturational stages have been identified before CAEPs become fully mature in young adulthood[27–31]. In early childhood, responses are typically biphasic and dominated by a broad P1 followed by N2. At around 8–9 years of age, the N1 and P2 peaks begin to emerge and the waveform becomes multiphasic. With age, P1 gradually decreases in amplitude and latency, while N1 increases in amplitude and decreases in latency until it becomes a mature discrete component in young adulthood[12,25,30–32]. Developmental findings for P2 are less consistent than those for P1 and N1[24,25,29,32]. Nevertheless, each peak is thought to reflect partly distinct aspects of cortical auditory processing[10,33].

Despite extensive research on auditory cortical development using CAEPs, four areas particularly relevant to the present study remain underexplored. First, most seminal developmental studies have used non-speech sounds, such as tones or clicks, to elicit CAEPs[12,23,24,27,30,34], while only a few have examined maturational changes evoked by speech sounds[26,29,31,35]. However, investigating the maturation of speech-evoked CAEPs in typically developing (TD) children offers a valuable tool for understanding the neurophysiological processes underlying the normative development of speech processing and provides insights into the neural encoding of speech in children at risk of neurodevelopmental delays[17,19,36]. Moreover, as speech-evoked CAEPs can be elicited during passive listening, this paradigm is suitable for individuals with neurodevelopmental differences for whom active task performance might be challenging.

Second, there is a paucity of studies examining frequency-specific differences in the maturation of speech-evoked CAEPs. Functional imaging studies show that auditory cortex is tonotopically organized, with different sound frequencies represented along spatial gradients across auditory cortical regions[37–41]. These frequency-specific cortical representations continue to mature and refine with age[4,42,43]. Auditory cortical potentials are sensitive to stimulus frequency and have been interpreted as reflecting, at least in part, the tonotopic organization of the underlying neural generators[10,26,33,44–46]. Thus, maturational changes in the tonotopic organization of auditory cortex may contribute to stimulus frequency-dependent developmental trajectories of speech-evoked CAEPs. Interestingly, behavioral studies suggest that auditory development is not uniform across frequency ranges. For instance, sensitivity to high-frequency pure tones (around 4000 Hz) is near adult-like by six months of age, whereas sensitivity to low-frequency pure tones (around 500 Hz) matures later, i.e., by early school age (see review[47]). Discrimination of high-frequency pure tones is almost adult-like by around age three, whereas discrimination of low-frequency pure tones continues to improve into the school years and does not reach adult levels until age 10[48]. However, these age-related improvements in frequency sensitivity, which vary by stimulus frequency, have not been directly linked to the maturation of speech cortical processing. Importantly, pure-tone sensitivity reflects auditory processing of relatively simple sounds and may rely more strongly on peripheral and subcortical auditory neural mechanisms than on auditory mechanisms involved in processing speech, i.e., primarily cortical processing[49–51]. Nevertheless, maturation of these earlier auditory processes may provide an important foundation for cortical processing of more complex sounds in those frequency regions, including speech[2,52,53]. Overall, frequency-specific findings from behavioral studies provide a supportive developmental context for testing whether cortical responses to speech sounds with different spectral profiles show different maturational trajectories.

In the present study, we were interested in capturing frequency-specific responses to speech-relevant stimuli. One approach to characterize frequency-specific speech processing is to use isolated phonemes, which are the smallest building blocks of speech sounds and exhibit dominant spectral energy in distinct frequency ranges[44,54]. Although some studies investigating auditory maturation have examined CAEPs in response to phonemes, very few have directly compared responses to phonemes with distinct frequency profiles[20,21,44,55,56]. We aimed to help address this gap in the research literature.

Third, studies investigating speech-evoked CAEPs have generally employed a group design and focused on a narrow age range, targeting either infants, children, adolescents or adults[13,20,26,28,29,44]. Examination of CAEPs across a wide age range, from childhood to adulthood, would provide a comprehensive picture of the entire maturational process throughout development. This has the potential to aid in early assessment of atypical auditory developmental trajectories, for example, in children with hearing difficulties or in individuals with neuro-maturational delays who are at risk for communication challenges.

Fourth, the relationship between the maturation of speech-evoked CAEPs and speech perception abilities remains poorly understood. Speech perception depends on the neural encoding of multiple aspects of speech sounds, such as frequency, amplitude, and timing cues, which are reflected in CAEP peak measures[19,57]. Thus, P1 and N1 obligatory responses are objective neurophysiological indices of early cortical processing that contribute to complex skills such as understanding speech[17,58,59]. Speech perception, including understanding speech in quiet and in degraded conditions, develops throughout childhood and reaches adult-like proficiency by late childhood and late adolescence, respectively, depending on the specific task and type of stimulus used[60,61]. Thus, the protracted maturation of CAEPs is accompanied by improvements in auditory perceptual skills throughout the developmental period[2,4,17]. However, developmental improvements in speech perception are only partly due to changes in auditory processing throughout development. Maturation of the cognitive and language systems also contributes to improvement in speech perception when listening in complex acoustic environments (see reviews[47,62,63]). The present study addresses a timely need to better understand the association between speech perception and CAEPs across development.

Very few maturational studies have specifically examined the relationship between speech perception and CAEPs in a population ranging from children to adults. Most previous studies have focused on specific age groups and yielded mixed findings (see reviews[19,57,64]). Differences in task stimuli, CAEP, and speech perception testing in quiet or real-world conditions, i.e., in the presence of background noise, sample size, age range of

participants, and their language and cognitive developmental stage may contribute to the lack of consistent findings[32,58,65]. Most notably, there might be frequency-specific differences in the association between cortical maturation and the development of speech perception skills. High-frequency sounds are known to be critical for speech understanding, particularly in the presence of background noise[66–68]. Thus, CAEPs evoked by high-frequency speech sounds might better predict performance on speech perception tests in degraded conditions than CAEPs in response to low-frequency sounds. Understanding how frequency-specific auditory processes develop and relate to the development of speech perception abilities is crucial for designing interventions that ensure access to optimal auditory input, such as with ideally fitted hearing aids and/or cochlear implants.

The goal of the present study was to address these gaps in the literature by evaluating the auditory maturational process using CAEPs in response to low-frequency (/m/) and high-frequency (/s/) phonemes in neurotypical individuals with no known hearing difficulties, ranging in age from 5 to 24 years. This comprehensive characterization of age-related changes in CAEP can serve as a benchmark to assess auditory maturational differences in individuals with hearing difficulties or neuro-maturational delays. We focused on the P1 and N1 peaks, which are reliable neurophysiological indices of auditory cortical maturation[26,30,31]. The following were the specific aims and hypotheses:

- To measure developmental trajectories of obligatory P1 and N1 peak measures in response to high-frequency (/s/) and low-frequency (/m/) sounds in neurotypical individuals (aged 5 to 24 years) with no known hearing difficulties. We hypothesized that younger children (5–8 year olds) would show an immature biphasic response, which would gradually transition to a triphasic response. Further, we hypothesized that P1 amplitudes and latencies would decrease while N1 would exhibit a decrease in latency and an increase in amplitude from early childhood to adulthood. Additionally, consistent with the development of behavioral sensitivity, we predicted that P1-N1 responses to high-frequency sounds would show signs of earlier maturation as compared to low-frequency sounds.
- To assess whether CAEPs in response to /m/ and /s/ stimuli presented in quiet conditions would be associated with speech understanding skills in quiet and in the presence of speech interferers. We hypothesized that mature CAEP measures (lower P1 and higher N1 amplitudes and shorter P1 and N1 latencies) would be associated with better speech understanding in quiet and in the presence of background speech interferers. Further, we explored whether the association between CAEPs and speech understanding would differ for low- and high-frequency stimuli.

Methods

Participants

Neurotypical children and adults ($n = 73$) were recruited from communities in and surrounding Madison, WI. Children ranged in ages from 5 to 17 years, while adults ranged in age from 18 to 24 years. Criteria for participation included English as a primary spoken language and no known hearing loss, confirmed with pure tone audiometry (at or below 20 dB HL in both ears at octave frequencies between 250 and 8000 Hz). Additional criteria for excluding participation were the presence of atypical neurological history, serious medical diagnoses, or developmental disabilities (e.g., autism spectrum disorder, intellectual disability, attention deficit disorder). Three participants were excluded from the study because their pure-tone air conduction thresholds did not meet the criteria. The final sample consisted of a total of 70 neurotypical participants: 48 children (mean age = 11.33 years, SD = 3.64; 29 females, 19 males) and 22 adults (mean age = 20.76 years, SD = 1.54; 16 females, 6 males). This sample size is broadly consistent with prior developmental studies examining CAEP maturation, that typically include sample sizes ranging from 50 to 120 participants[12,24,26,27,29–31,69]. For selected descriptive and group-based analyses, participants were organized into four age groups: younger children (5–8 years, $n = 16$), older children (9–12 years, $n = 16$), adolescents (13–17 years, $n = 16$), and adults (18–24 years, $n = 22$). Each child participant was accompanied by a parent or legal guardian, and written informed consent and verbal assent were obtained before participation. All adult participants provided written informed consent. Because the present study was part of a larger study involving multiple measures, participants completed testing across different days, ranging from 2 to 5 study visits. This study was approved by the Institutional Review Board (Health Sciences IRB Protocol #2022 – 0610 Approval date: 6/14/2022) at the University of Wisconsin-Madison, and all experiments were conducted in accordance with relevant guidelines and regulations.

EEG measures

Stimuli

Auditory stimuli consisted of naturally produced /m/ and /s/ phonemes created from speech samples 'ama' and 'asa', which were spoken by the same adult male talker and recorded with a sampling frequency of 44.1 kHz. Each stimulus had a duration of 80 milliseconds (ms), including 15 ms of cosine squared ramps (Fig. 1). The speech sounds /m/ and /s/ have a spectral emphasis in the low-, and high-frequency regions (spectral centroid ~ 200 Hz, and ~ 6000 Hz, respectively).

EEG recording

EEG data were acquired using a 128-channel Hydrocel Geodesic Sensor Net connected to a NetAmps 400 amplifier and Net Station 5.0 software (Magstim Inc, USA). The vertex channel (Cz) served as the reference during data collection. The impedances of all channels were kept at or below 50 kOhms and EEG signals were acquired at a sampling rate of 1000 Hz. All recordings were conducted in a standard IAC (Industrial Acoustics Company) sound-attenuated booth with an ambient temperature maintained at 68 °F. Auditory stimuli were presented using EPrime 3.0 software (Psychology Software Tools, USA). To ensure accuracy and precision of

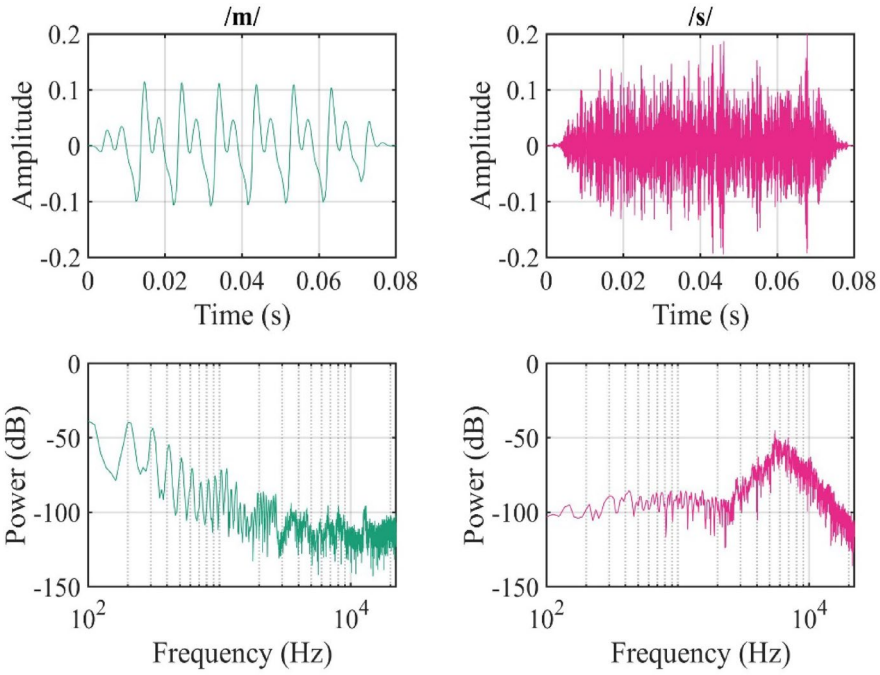


Fig. 1. Waveforms and power spectra of /m/ and /s/ stimuli.

stimulus onset time in synchronization with EEG, the stimuli were routed through a StimTracker (Cedrus, San Pedro, CA, USA) that was connected to the earphones, and the EEG amplifier.

During the EEG session, participants passively listened to auditory stimuli while watching a silent video, chosen by them from a list of age-appropriate videos. Participants were instructed to ignore the test stimuli, focus on the video, and sit as still as possible. Stimuli were presented monaurally to one ear at a time at 65 dB SPL using ER-2 insert earphones (Etymotic Research). During the testing for one ear, the contralateral ear was not occluded. The order of ear testing (right or left) was counterbalanced across participants. Both /m/ and /s/ phonemes were randomly presented (150 trials/phoneme), with an interstimulus interval (ISI) ranging from 1000 to 2000 ms. The primary tester continuously monitored the EEG data quality during acquisition. A second tester sat in the participant room to closely observe the participant for any major movements. Recordings were paused if there were significant movement artifacts. The testing was resumed once the participant was ready and able to sit still. Testing took around 7–8 min per ear. Prior to our EEG task, participants completed a resting state task where they were asked to sit still with their eyes open and then closed three times for 1 min each. However, note that resting EEG data are not discussed here. The entire EEG session, including cap placement, impedance checking, data acquisition, and breaks between different conditions lasted on average 1.5 hours.

EEG data preprocessing

EEG preprocessing was performed offline using custom scripts in EEGLAB v2023.1[70] within the MATLAB v2021b environment (Mathworks, Massachusetts, USA). Raw data were filtered using a low-pass Finite Impulse Response (FIR) filter at 30 Hz and a high-pass FIR filter at 0.5 Hz, and downsampled to 512 Hz. The clean_rawdata plugin v2.91, implementing the Artifact Subspace Reconstruction (ASR) algorithm, was applied to discard poor quality segments[71,72]. Channels were rejected if they were flat for over 5 s, showed excessive line-noise ($z > 4$) relative to the recording, or were not strongly correlated with neighbors ($r < 0.80$). For calibration, data were high-pass filtered (0.25–0.75 Hz transition band), and transient bursts were identified at 20 standard deviations. Artifact windows were rejected if over 25% of channels were contaminated and only extreme high-power segments were rejected. Missing channels were interpolated using spherical methods, and the data were re-referenced to the average.

On average, adults had 4.9% bad channels, compared to 8.1% in children. All bad channels were interpolated. Supplementary Table 1 provides detailed descriptive statistics for the number of interpolated channels, summarized separately for children and adults. We established an a priori criterion of 15% or fewer interpolated channels to include a given participant in data analyses. All participants met the criteria except four children who had between 15 and 20% channels interpolated. However, we decided to retain these data because the interpolated channels were not spatially clustered and the ERP waveforms were visually comparable to those of other participants in the same age group. We performed a sensitivity analysis by re-running our age-effect models after excluding these four children, and the results remained unchanged.

The artifact-free continuous data were then epoched from −100 to +500 ms relative to the onset of the auditory stimulus (/m/ and /s/ phonemes) and baseline-corrected using the pre-stimulus period (−100 to 0 ms). Only data from participants who had at least 50 clean trials for each phoneme in each ear were included in statistical analyses, in line with recommended thresholds[73,74].

EEG data analyses

Our primary analyses focused on P1 and N1 peak amplitude and latency measures to test a priori hypotheses and to facilitate comparison with previous developmental studies. Cz was selected as the primary location of interest because P1 and N1 responses are typically most prominent over frontocentral scalp regions, and vertex/Cz recordings have been widely used in developmental CAEP studies to characterize maturational changes[20,26,32,65,75,76]. To characterize the broader scalp distribution of developmental CAEP effects, we also examined CAEP waveforms at other midline electrodes, Fz and Pz, together with three midline regions of interest (ROIs) defined as electrode clusters centered on Cz, Fz, and Pz. Specifically, we defined a Central ROI (E7, E31, E55, E80, E106, and E129: around Cz), a rontal ROI (E4, E5, E10, E11, E12, E16, E18, and E19: around Fz), and a arietal ROI (E61, E62, E67, E71, E72, E76, E77, and E78: around Pz). For each ROI, ERPs were averaged across electrodes prior to P1 and N1 peak detection. Averaging ERPs across electrodes within an ROI can provide a potentially more stable and reliable estimate of CAEP response than reliance on a single electrode alone, while also offering a view of regional scalp patterns associated with maturational changes in CAEPs[77,78].

Peak based analyses were conducted to directly test our hypotheses, particularly at Cz. However, this approach necessarily required analytic decisions regarding electrodes of interest, time windows, and peak quantification procedures which limit advantages associated with high-density electrode arrays. Therefore, to maximize data analyses, we also performed complementary data-driven, whole-scalp mass-univariate analyses[79]. This approach allowed us to evaluate developmental effects across all electrodes and time points[80].

In summary, the EEG analyses comprised two complementary approaches: (1) hypothesis-driven primary analyses of P1 and N1 peak amplitude and latency, with Cz as the primary site for detailed reporting and Fz, Pz, and the three ROIs providing broader spatial context; and (2) data-driven whole-scalp mass-univariate analyses across all electrodes and time points.

Primary analyses of P1 and N1 peak measures

Epoched EEG data were processed for peak based analysis using ERPLAB plugin v10.04[81] in EEGLAB. P1 and N1 peak amplitudes and latencies were extracted using automated peak detection with the *pop_geterpvalues* function within ERPLAB[81]. For all participants, the P1 and N1 peaks were defined as the most positive or negative deflection occurring within 30–110 ms and 70–150 ms, respectively. These time windows were selected based on prior auditory maturation studies[12,26,29,31]. Notably, the algorithm identified a peak only if the value was higher for P1 or lower for N1 than the preceding and subsequent three consecutive data points. For both P1 and N1, the baseline-to-peak amplitude and latency from stimulus onset values were extracted for each participant for further analyses.

For the primary analyses at Cz, automated peak detection was further verified through visual inspection of each subject's grand-averaged waveforms using the ERPLAB measurement tool before extracting peak amplitude and latency[69,82]. If visual inspection indicated that a peak fell outside the predefined window, the window was manually adjusted. If the peak was misidentified within the predefined window, the appropriate peak was manually selected[13,28]. All manual adjustments were carried out by the first author, repeated to ensure consistency, and verified by the last author. Overall, manual adjustment was required in 5 of 88 adult ear- and phoneme-specific datasets (5.68%) and 29 of 192 child ear- and phoneme-specific datasets (15.10%). See Supplementary Table 2 for details. To determine whether the findings were sensitive to the peak-detection method, we conducted sensitivity analyses by fitting CAEP-age association models to data derived from both the manually verified and fully automated procedures. The plots from the fully automated procedure are shown in Supplementary Fig. 1. Because both approaches yielded broadly similar developmental patterns and comparable statistical conclusions at Cz, only the automated approach was used for developmental analyses at the additional scalp sites.

CAEPs were recorded monoaurally to better serve the needs of our larger study, which includes populations with hearing loss and neurodevelopmental delays, in whom between-ear differences in hearing sensitivity are more likely and may differentially influence CAEP morphology, as well as peak amplitudes and latencies. For the present sample consisting of typically developing, normal-hearing individuals, we did not expect any systematic between-ear differences. Nevertheless, we verified this by comparing P1 and N1 peak amplitudes and latencies between ears using paired-samples t-tests. No significant between-ear differences were observed in amplitude and latencies (statistical details are provided in Supplementary Table 3). As a result, to streamline the analysis and reduce the number of comparisons, P1 and N1 values were averaged across both ears for subsequent statistical analyses. After screening for an adequate number of artifact-free trials, EEG data from 70 participants were included in the final analysis. Supplementary Table 4 provides the average number of accepted trials per phoneme for all age groups.

Whole-scalp mass-univariate analyses

Mass-univariate cluster-based permutation analyses were performed separately for /m/ and /s/ using subject-level CAEP data averaged across ears. All 128 electrodes and the data from 30 to 250 ms post-stimulus interval were included, without pre-specifying any electrodes or narrow analysis windows of interest. Developmental differences across the four age groups were first assessed using an omnibus cluster-based permutation F-test, followed by pairwise age-group contrasts corrected for multiple testing. For visualization, "early" and "late" temporal peaks were identified within the broad, significant spatiotemporal cluster. For the time point corresponding to each peak, a local ROI was defined around the electrode showing the strongest age-related effect. These ROIs were used to visualize waveform morphology and developmental changes in responses. Full implementation of mass-univariate analyses is detailed in the Supplementary Methods.

Speech understanding task

Stimuli

A set of 25 bisyllabic words (spondees) spoken by a male talker was used as target stimuli[83]. The interferer stimuli consisted of two talker speech interferers generated by superimposing two recordings of a single male talker speaking different sentences from the Harvard IEEE corpus[61,83]. The interferer stimuli did not have any silent gaps or pauses.

Task procedure

The Children's Realistic Index for Speech Perception (CRISP), a closed-set four-alternative forced-choice (4-AFC) task, was used to measure speech understanding in quiet and three different conditions with background interferers[83]. Testing was completed in a single-walled sound-treated IAC booth. Target stimuli were always presented from a loudspeaker in front of the listener (0° azimuth). Each auditory target word had a corresponding picture. On each trial, four pictures were presented on a touchscreen monitor, such that one of the pictures matched the auditory stimulus. A trial began with an alerting phrase ("Ready?") preceding the target word, after which the four pictures were displayed. Participants were asked to select the picture that matched the perceived target word. Following each incorrect response, feedback was provided.

To represent different real-world listening conditions in which interferers might come from different directions, we implemented three different conditions with interfering speech: Front (interferers co-located with the target); Right (interferers at 90° azimuth to the right of the participant); Left (interferers at 90° azimuth to the left of the participant). Loudspeakers were located at 1.2 m from the center of the participant's head. In total, there were four listening conditions (Quiet, Front, Right, and Left), and testing was repeated twice for each condition, in randomized order. During each test run, the target stimulus level was varied adaptively with a starting level of 60 dB SPL. Initially, following each correct response, the target level decreased by 8 dB, and following the first incorrect response, a modified 3-down/1-up rule was used (see Ref.[83] for detailed adaptive tracking rules). The level of interfering stimuli was fixed at 55 dB SPL. This adaptive protocol has been used extensively in previous speech understanding studies in adults and children aged 3 years and older[61,83–85]. Participants completed a familiarization session before testing began to ensure familiarity with the target words and to confirm their ability to associate each word with its corresponding picture. The protocol specifies that if a given target word was unfamiliar to a participant, that word was removed from the list of options for that participant. While a minimum familiarity with 15 target words was required to qualify, all participants successfully identified the full set of 25 words, allowing the entire set to be used in testing.

Speech reception thresholds (SRTs) were determined using a logistic function fitted to data using the MATLAB "psignifit" toolbox (version 4)[86], as described by Wichmann and Hill[87], and similar to our prior analysis approach for these type of data[61,83–85,88]. The SRT corresponded to the 79.4% correct point on the psychometric function, with the guessing rate (γ) fixed at 0.25 and the lapse rate (λ) capped at 0.06. Thresholds from all runs within a condition were averaged to produce a single value per participant.

Statistical analysis

Our first aim was to characterize age-related changes in CAEPs (P1 and N1 amplitudes and latencies) in response to each phoneme (/m/ and /s/). Since CAEPs may exhibit non-linear changes with age[12,13], we modeled the relationship of each CAEP measure with stimulus type and age using both generalized additive models (GAMs) and linear mixed-effects models (LMMs), implemented in mgcv and lme4 packages, respectively, with linear, polynomial, and logarithmic terms for age[89–91]. GAMs were included to capture both linear and potential non-linear age-related changes without assuming a specific shape of the relationship between age and CAEP measures[92,93]. Because each participant contributed repeated CAEP measurements across stimuli, the GAM/LMM framework leveraged the within-subject structure to improve estimation precision for age-related effects and neural–behavioral associations, with model complexity controlled via penalized smoothness (GAMs) and partial pooling (LMMs). In the GAM analyses, age-related trajectories were allowed to vary by stimulus and were modeled flexibly using penalized shrinkage cubic spline smooths ($k = 4$), enabling detection of both linear and nonlinear developmental patterns while avoiding overfitting. The modest basis dimension was chosen to capture broad developmental trends, and diagnostic checks indicated that it was adequate. Model selection was based on lower Akaike Information Criterion (AIC) and higher conditional R^2 for LMMs and higher deviance explained for GAMs. GAMs consistently explained the most deviance and are therefore reported here. Alternative model specifications considered during model selection are reported in Supplementary Results (section: Additional Results for Associations Between Age and P1 and N1 Amplitude and Latency at Cz). Results of the GAM model are described in terms of effective degrees of freedom (edf) for each smooth term, and the associated approximate significance tests[94]. The edf summarizes the complexity of the estimated smooth after the smoothing penalty has been applied. An edf value of ~1 indicates the relationship is linear, whereas larger edf values indicate higher non-linearity in the fit[94,95]. We also conducted secondary analyses by examining the first derivative of the fitted GAM age smooth functions to identify periods of significant developmental change[92,96]. This estimate provided an estimate of the age at which P1 and N1 measures approached stable trajectories that may reflect mature response patterns (Supplementary Table 5; Supplementary Fig. 2).

To complement these models with age as a continuous variable, we also conducted group-based comparisons using the four developmental age groups described earlier in the Participants section. These age groups (5–8, 9–12, 13–17, and 18–24 years) were created based on prior literature documenting key maturational changes in P1 and N1 waveform characteristics[12,26,30,31]. Around 7–8 years of age, N1 begins to emerge with long ISIs (1000 ms and more), and by 9–10 years, most children exhibit reliable N1 peaks. By ~12 years of age, a stable triphasic CAEP waveform is typically observed. From age 13 onwards, CAEPs continue to mature gradually, and by adulthood, N1 is considered fully developed. Therefore, the age groups in our study reflect these meaningful

stages of auditory cortical maturation. Age group data were analyzed using LMMs with fixed effects for age group, stimulus type, and their interaction. Random intercepts for subjects were included, and Holm correction was applied to all post hoc pairwise comparisons.

To address our second aim of exploring the relationship between CAEPs and behavioral speech understanding (SRTs), we first computed zero-order correlations between CAEP measures, age, and SRTs in each listening condition (Quiet, Front, Right, Left). We also examined bivariate correlations between CAEPs and SRTs, correcting for multiple comparisons. To account for age-related developmental factors that may affect speech understanding task performance, we employed LMMs with SRTs as the dependent variable, CAEP measure, listening condition, and their interaction as fixed effects, age as a covariate, and a random intercept for subjects. Because CAEP measures are not independent, we ran separate LMMs for each measure. Including both phonemes within a single model resulted in convergence issues, i.e., the model terminated with an error; therefore, separate models were run for /m/ and /s/ stimuli. Given the exploratory nature of this aim, we did not correct for multiple testing across all models. Note that for one participant, SRT data were not available, and were therefore not included in the association analyses. All predictors were mean-centered, and model residuals were examined for any violation of normality and homoscedasticity assumptions. All statistical analyses were conducted using R software (version 4.2.2; R Core Team 2022).

Results

We first provide a descriptive visualization of grand average waveforms across scalp regions to show the spatial distribution of age-related maturational changes in CAEP waveform morphology. We then present the primary analyses of P1 and N1 peak measures at Cz, the main analysis site for directly testing our hypotheses. We also briefly summarize parallel findings on P1 and N1 peak measures from other scalp locations. Finally, we summarize the findings from whole-scalp mass-univariate analyses.

Descriptive overview of developmental changes in CAEP morphology

Figure 2 shows grand-average responses for all age groups at Fz, Cz, and Pz, together with the rontal, entral, and arietal ROIs. Developmental differences in CAEP morphology were evident across regions. The ROI waveforms closely resembled those obtained from their corresponding representative electrodes (i.e., rontal ROI and Fz, entral ROI and Cz, arietal ROI and Pz), suggesting that the single midline channel broadly captured the corresponding regional activity. For both phonemes, progressive age-related differences were pronounced over Fz, Cz, and the rontal and entral ROIs. At these sites, the waveforms in younger children showed an immature biphasic pattern with a large positive P1 peak with a small N1 notch, and gradually became more triphasic and adult-like with the clearer emergence of N1 and P2 peaks with age; this contrast was sharpest at Cz. In adults, N1 and P2 peaks were clearly defined at these sites. At Pz and the Parietal ROI, the developmental pattern differed from that seen at frontal and central sites. Rather than showing clear progressive maturational changes across all four age groups, the two children groups appeared very similar to each other, with a relatively distinct N1 and a larger later positive peak (P2), whereas adolescents and adults showed very similar waveforms with less distinct P1–N1–P2 morphology and relatively less defined N1 and P2 peaks.

In addition, closer examination of the grand-average CAEP waveforms revealed stimulus-specific morphological differences at frontal and central sites, whereas such differences were not clearly evident at parietal sites. At central and frontal sites, once the N1 peak was more clearly developed in adolescents and adults, N1 appeared larger for /m/ than for /s/. Further, at central sites, the grand-average waveform for /s/ in 5–8-year-old children was largely biphasic, with a broad P1 and only a small notch-like N1 deflection, whereas the waveform for /m/ showed a relatively larger N1 notch, although it remained immature compared with older children, adolescents, and adults. At frontal sites, grand average waveforms in 5–8-year-old children were predominantly biphasic for both phonemes, with no clear N1 notch, and this immature morphology largely persisted in 9–12-year-old children.

Scalp topography maps at the grand average P1 and N1 peaks for each group are shown in Fig. 3. These maps further illustrate developmental changes in the spatial distribution and magnitude of the CAEP response. For children aged 5–8 years, P1 was stronger in frontocentral regions for /m/ and /s/. With increasing age, the P1 response shifted anteriorly and weakened. The N1 response also shifted developmentally, from a posterior and parietal distribution in the younger children, to a frontocentral distribution with age. In adults, the N1 was prominent and centrally focused for both phonemes. Notably, within this N1 developmental pattern, the response to /m/ appeared to show this shift earlier than the response to /s/.

Together, the grand average waveforms and scalp topographies reveal marked age-related changes in both the morphology and scalp distribution of speech-evoked CAEPs, characterised by a reduction in P1 response and concomitant increases in N1 response at fronto-central electrodes.

Developmental changes in P1 and N1 amplitude and latency across different age groups

To characterize age-related maturational changes in P1 and N1 responses to /m/ and /s/ stimuli, the amplitude and latency of P1 and N1 peaks at Cz (our main region of interest) were compared across different age groups of children and adults (Fig. 4).

P1 amplitude and latency

Significant main effects of age group were observed (Fig. 4A, B; amplitude: $F(3,65) = 30.92$, $p < 0.001$; latency: $F(3,65) = 28.94$, $p < 0.001$). There was a significant main effect of stimulus for P1 amplitude ($F(1,65) = 8.34$, $p = 0.005$), but no significant age group x stimulus interaction, indicating that age-related changes in P1 amplitude and latency were not different for /m/ and /s/ stimuli.

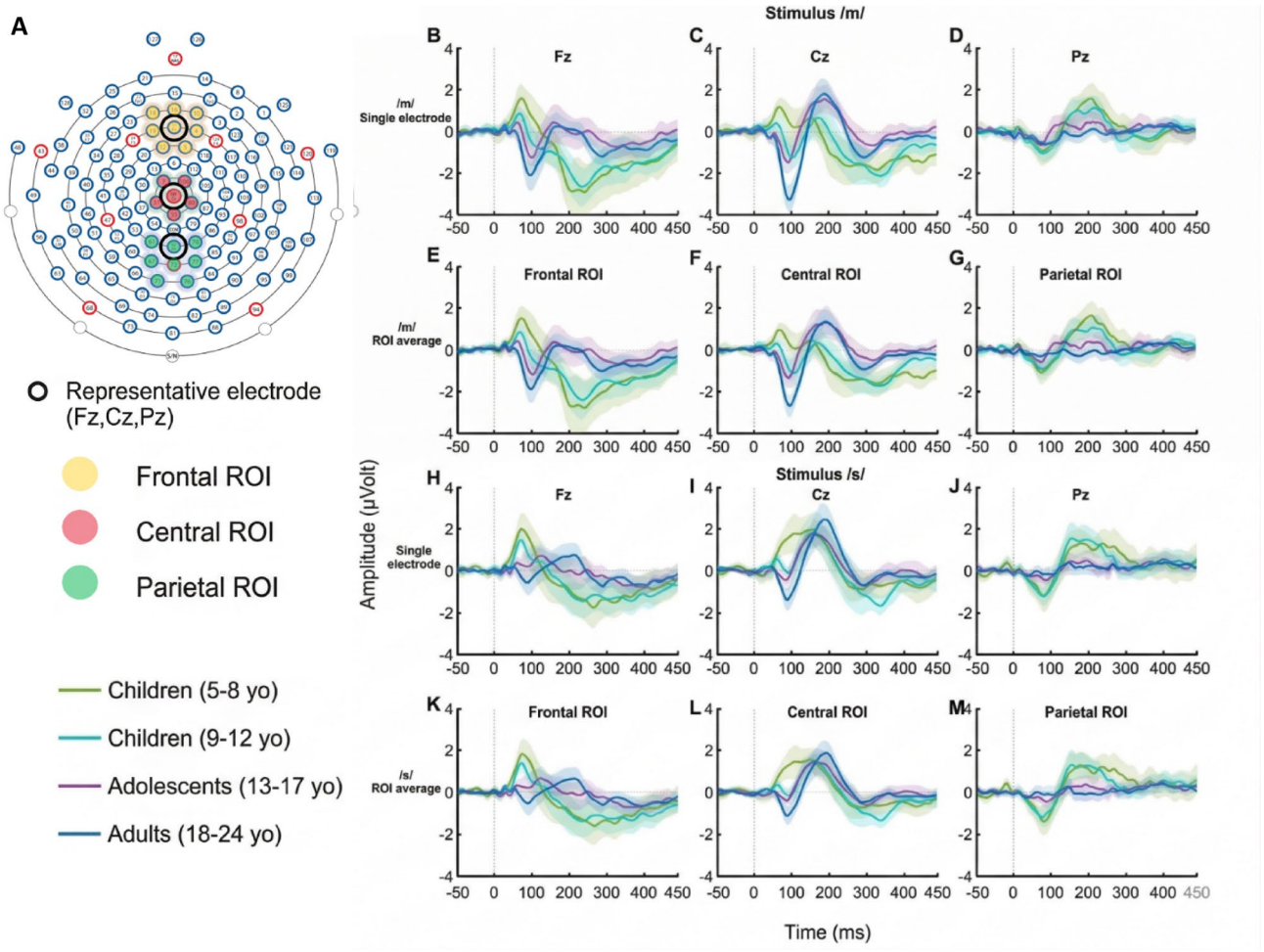


Fig. 2. Grand-average waveforms at representative midline electrodes and regional ROIs for /m/ and /s/. The electrode map (A) shows the representative midline electrodes (Fz, Cz, Pz) and the Frontal, entral, and arietal ROIs used for descriptive visualization. Waveforms (B-M) are shown separately for /m/ and /s/ at the single electrodes and corresponding ROI averages for four age groups (5–8 years, 9–12 years, 13–17 years, and 18–24 years). Frontal ROI: E4, E5, E10, E11/Fz, E12, E16, E18, E19; Central ROI: E7, E31, E55, E80, E106, E129/Cz; arietal ROI: E61, E62/Pz, E67, E71, E72, E76, E77, E78. Shaded bands indicate 95% confidence intervals.

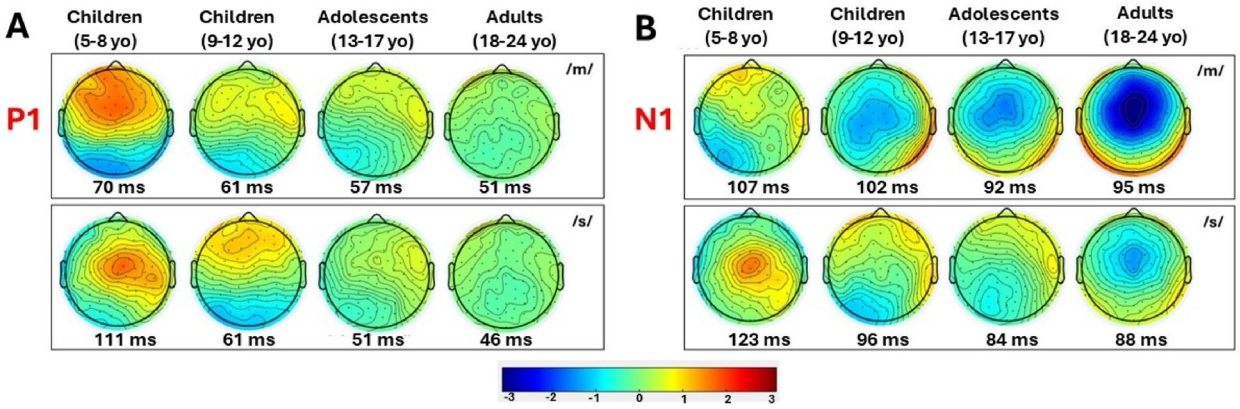


Fig. 3. Scalp topographies for P1 (**A**) and N1 (**B**) across age groups and stimulus conditions. For each map, the plotted time point corresponds to the peak latency measured from the grand-average Cz waveform, and the latency value is displayed on the map. The maps illustrate developmental changes in P1 and N1 response distribution and magnitude across age groups and stimuli. Warmer colors indicate positive voltage, and cooler colors indicate negative voltage.

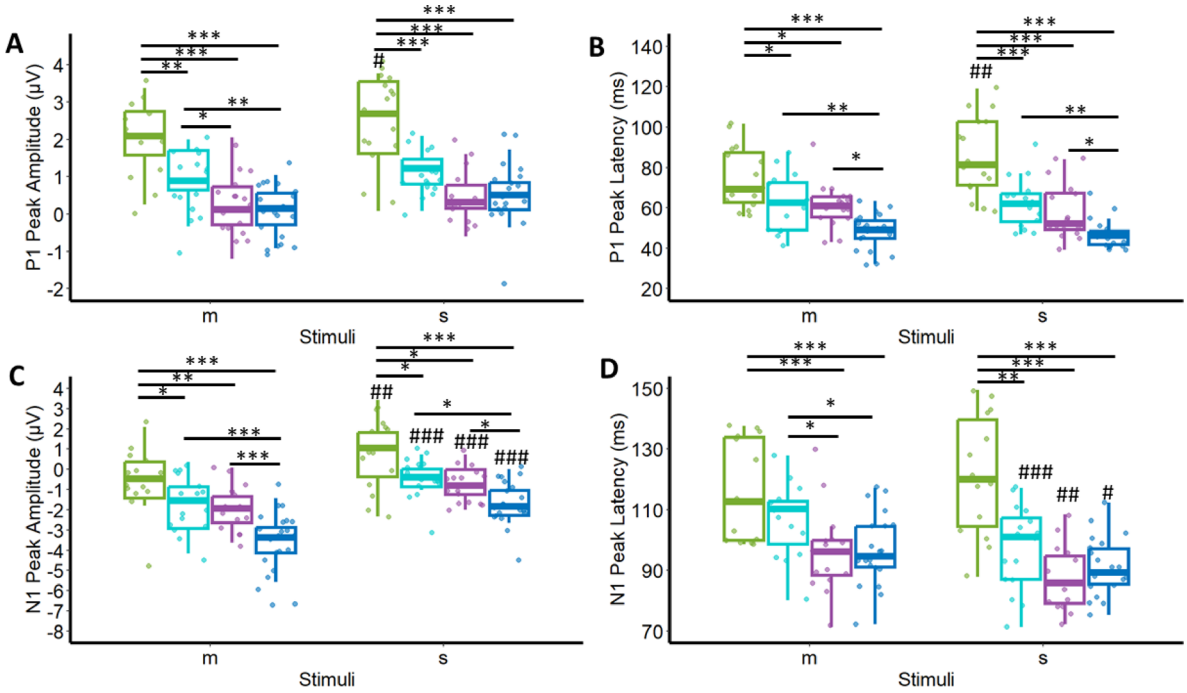


Fig. 4. Age related differences in CAEPs for /m/ and /s/ stimuli at Cz. Box plots show the distribution of P1 peak amplitude (**A**), P1 peak latency (**B**), and N1 peak amplitude (**C**) and N1 peak latency (**D**) across four age groups for both /m/ and /s/ stimuli. Individual data points are overlaid on each box plot. Symbols: Differences between age groups (*), Differences between stimuli (#), The number of symbols indicate p values, for example, $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. See Supplementary Results (section: Additional Results for Developmental Changes in P1 and N1 Amplitude and Latency Across Age Groups at Cz) for statistical information on pairwise comparisons.

N1 amplitude and latency

Significant main effects of age group were found (Fig. 4C, D ; amplitude: $F(3,65) = 18.20$, $p < 0.001$; latency: $F(3,65) = 15.62$, $p < 0.001$), indicating age-dependent changes in both measures. A significant main effect of stimulus was found for amplitude ($F(1,65) = 79.18$, $p < 0.001$) and for latency ($F(1,65) = 13.57$, $p < 0.001$), suggesting that N1 amplitude and latency varied by stimulus type. A significant age group x stimulus interaction was found for N1 latency $F(3,65) = 4.57$, $p = 0.006$). There was no significant age group x stimulus interaction for N1 amplitude.

The corresponding Supplementary Results (section: Additional Results for Developmental Changes in P1 and N1 Amplitude and Latency Across Age Groups at Cz) provides statistical details for all pairwise comparisons of stimulus and age-group differences.

Associations between age and P1 and N1 amplitude and latency

In our analyses examining age-related changes in CAEPs at Cz, GAM models best captured non-linear age trends and consistently explained the highest deviance. Across all our GAM models, the explained deviance ranged from 74% to 84%, indicating strong model fits (Fig. 5). Subject-level random effects were significant for all CAEP measures (effective degrees of freedom [edf] > 32.6, $p < 0.001$), highlighting substantial individual variability in auditory maturation.

P1 amplitude and latency

Age-related decreases in P1 amplitude were clearly non-linear, for both /m/ stimuli (edf = 2.28, F = 46.6, $p < 0.001$) and /s/ stimuli (edf = 2.47, F = 56.2, $p < 0.001$), suggesting a non-linear maturational trajectory. The relationship of P1 latency with age was significant for both stimuli but somewhat smoother for /m/ stimuli (/m/: edf = 1.45, F = 23.6, $p < 0.001$; /s/: edf = 2.03, F = 51.4, $p < 0.001$). The secondary analyses of age estimates suggested earlier maturation for /s/ than for /m/ for P1 amplitude (13.9 vs. 17.1 years), and P1 latency (17.9 vs. 19.2 years), see Supplementary Table 5 and Supplementary Fig. 2 for details.

N1 amplitude and latency

Unlike P1, N1 amplitude increased nearly linearly with age for both stimuli (/m/: edf = 1.35, F = 42.3, $p < 0.001$; /s/: edf = 1.20, F = 19.8, $p < 0.001$) and showed stimulus-specific differences. To further explore potential stimulus-specific differences in maturation, a linear regression model revealed a significant age × stimulus interaction ($\beta = 0.0595$, $p = 0.045$), indicating steeper age-related increases in N1 amplitude for /m/ than for /s/. This suggests that N1 responses to /m/ continue to strengthen across development, while responses to /s/ follow a shallower

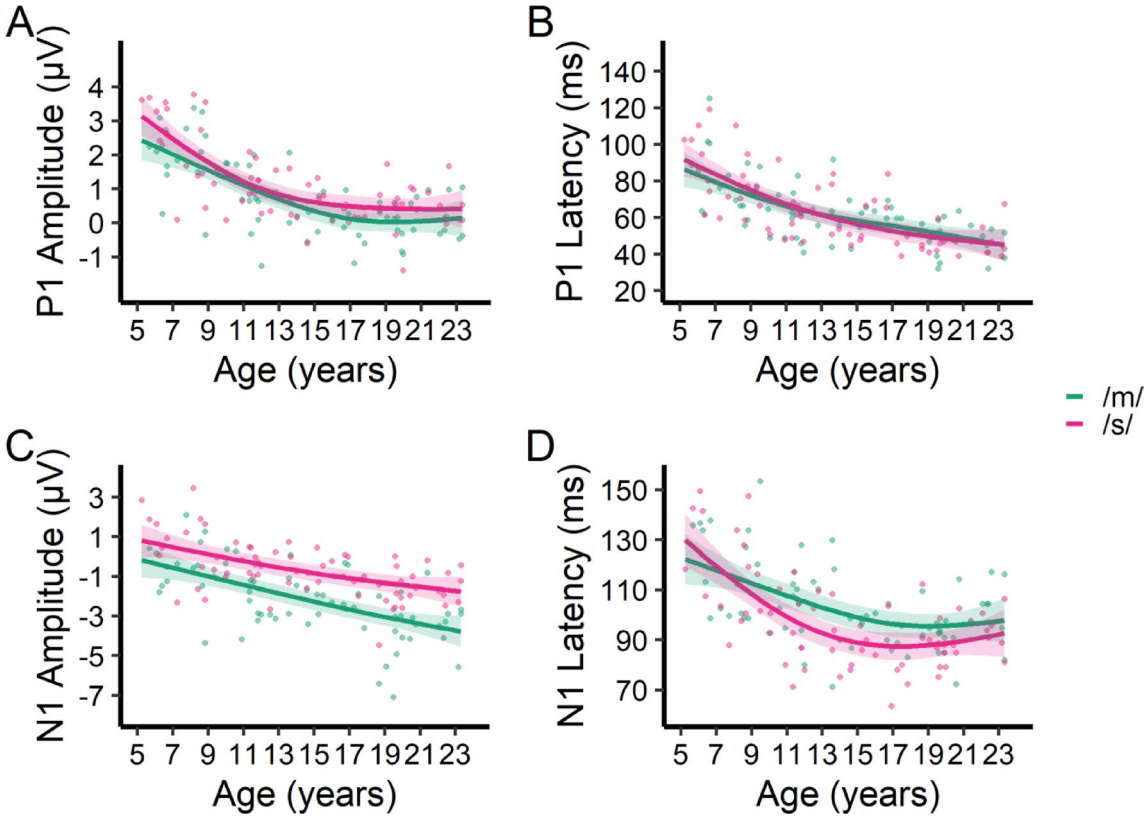


Fig. 5. Relationships between age and CAEPs for /m/ and /s/ stimuli at Cz. GAM model fits showing developmental trajectories of P1 and N1 amplitude and latency across age for /m/(green) and /s/(magenta) stimuli. Shaded regions represent 95% confidence intervals. Panels illustrate age-related changes for: (**A**) P1 amplitude, (**B**) P1 latency, (**C**) N1 amplitude, and (**D**) N1 latency.

trajectory and remain less prominent even in adulthood. Although the model with a quadratic term for age yielded a slightly lower BIC, the age-squared effect was not significant, so the model with a linear term was retained as the final model for better interpretability. Details of model comparisons, including models with linear and quadratic terms, are summarized in Supplementary Results (section: Additional Results for Associations Between Age and P1 and N1 Amplitude and Latency at Cz). N1 latency showed non-linear relationships with age for both stimuli (/m/: edf = 2.16, F = 26.1, $p < 0.001$; /s/: edf = 2.30, F = 52.3, $p < 0.001$). The secondary analyses of age estimates suggested earlier maturation for /s/ than for /m/ for N1 amplitude (17.9 vs. 19.7 years), and N1 latency (14.0 vs. 15.8 years), see Supplementary Table 5 and Supplementary Fig. 2 for details.

P1 and N1 amplitude and latency at other sites

Results of the GAM models for P1 and N1 amplitude and latency at Fz, Pz, and the Central, rontal, and arietal ROIs are presented in the Supplementary Results (section: Additional Results for Associations Between Age and P1 and N1 Amplitude and Latency at Fz, Pz, Central, rontal and Parietal ROIs), Supplementary Tables 6–7, and Supplementary Figs. 3–7. Overall, the findings indicate that, as observed at Cz, age-related changes in P1 and N1 peak measures were robust and consistent at Fz, and within the Central and Frontal ROIs, with significant associations with age observed for all CAEP measures. By contrast, at Pz and within the Parietal ROI, age-related changes were weaker and selective, with significant findings limited to only N1 amplitude and latency for /s/, with the pattern being opposite to that observed at Cz, i.e., an age-related decrease in N1 amplitude and increase in latency.

Relationship between CAEPs and Speech reception thresholds (SRTs)

To examine the functional relevance of developmental variation in cortical auditory responses, we next tested whether individual differences in CAEP measures at Cz were associated with speech understanding performance across listening conditions.

The initial step was to examine zero-order correlations between all CAEP measures at Cz (P1 and N1 amplitudes and latencies), SRTs in each listening condition, and age. All SRT and CAEP measures were significantly correlated with age. Supplementary Fig. 8 illustrates the linear relationships between pairs of variables and their Spearman correlation coefficients and p-values, as well as histograms of each variable. Pairwise Spearman correlations between SRTs and CAEPs were then examined, following correction for multiple comparisons (Supplementary Table 8). Except for the relationship between N1 and P1 amplitudes with SRTs in Quiet for /s/, SRTs in all listening conditions were significantly correlated with CAEPs. However, these bivariate

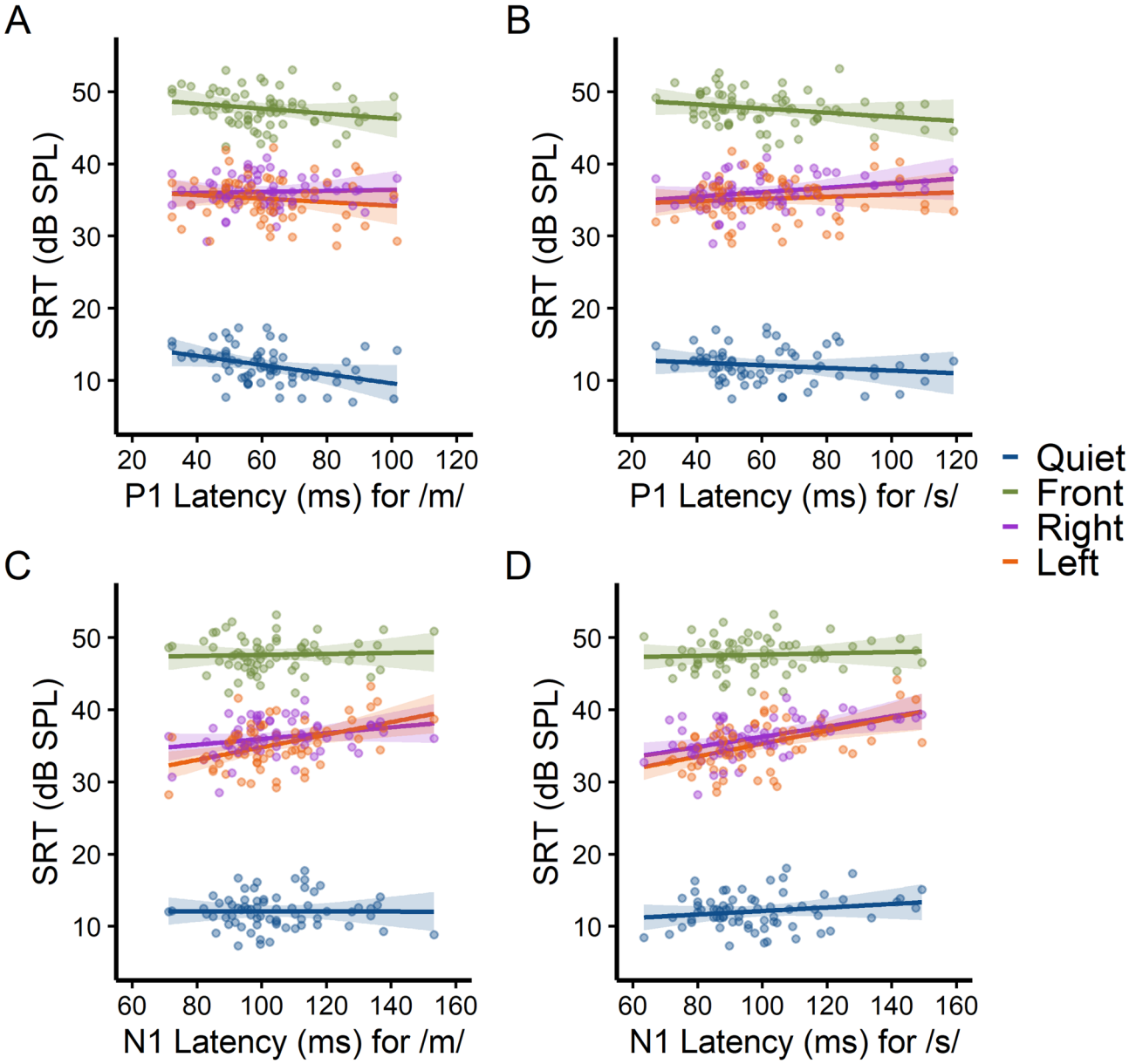


Fig. 6. Relationships between CAEP latencies and SRTs for /m/ and /s/ stimuli. Scatterplots and regression lines show the associations between SRTs and P1 (A, B) and N1 (C, D) peak latencies for /m/ and /s/ stimuli across the four listening conditions, based on the location (if any) of the interferers. Shaded regions represent 95% confidence intervals. Age was included as a covariate in the linear mixed-effects models.

relationships between P1 and N1 measures and SRTs could be driven by age, as both CAEP and SRT measures show age-related changes.

We therefore used linear mixed-effects models to examine the relationship between SRTs and CAEPs across listening conditions (Quiet, Front, Right, Left), including age as a covariate. Figure 6 shows the relationships for P1 and N1 latencies with SRTs in Quiet and in the presence of co-located (Front) and separated (Right and Left) interferers for /m/ and /s/ stimuli. Note that post hoc (simple-slope) comparisons are reported as exploratory and were not corrected for multiple comparisons.

Overall, the primary finding was that N1 latency evoked by the high-frequency phoneme (/s/) was significantly associated with SRTs in both spatially separated interferer (masker) conditions. Specifically, for /s/ stimuli, N1 latency significantly predicted SRTs ($F(1,66) = 7.083$, $p = 0.009$, $\eta^2_p = 0.0961$), and there was a main effect of condition ($F(3,200) = 77.74$, $p < 0.001$, $\eta^2_p = 0.537$). The N1 latency x condition interaction was also significant ($F(3,200) = 4.681$, $p = 0.004$, $\eta^2_p = 0.065$). Post hoc comparisons (uncorrected) revealed significant associations between N1 latency and SRTs in the Right ($p = 0.0029$) and Left ($p = 0.0003$) conditions, but not in the Front ($p = 0.712$) or Quiet ($p = 0.301$) conditions.

In contrast, P1 amplitude, N1 amplitude, and P1 latency did not show significant main effects as predictors of SRTs for either stimulus (Supplementary Fig. 9), although expected main effects of listening condition were observed across models. Statistical details of the null findings are reported in Supplementary Results (section: Additional Results for Relationship between CAEPs and Speech Reception Thresholds (SRTs)).

Whole-scalp mass-univariate analyses of CAEP developmental effects

We performed mass-univariate analyses to investigate the spatial distribution and timing of the developmental differences in CAEP responses. Cluster-based permutation F-tests across the four age groups, spanning all electrodes and the 30–250 ms post-stimulus interval, identified a broad significant spatiotemporal cluster for both phonemes (Supplementary Fig. 10). Pairwise cluster-based permutation tests further showed that all six age-group contrasts survived Holm correction for both phonemes, with the strongest age effects generally involving adults and the children groups. Together, these findings indicate robust age-related differences in CAEP response amplitude across much of the scalp, involving 124 electrodes and spanning a broad post-stimulus window (~31–250 ms) for both phonemes.

Descriptive follow-up analysis of the omnibus age effect (Supplementary Figs. 11–13) showed that, in the early window (31–145 ms), the strongest age-related effect was centered over frontocentral electrodes (E13 for both phonemes), whereas in the late window (145–250 ms), it was centered over more lateral electrodes (E117 for /m/ and E116 for /s/). Notably, the early peak ROIs included Cz. Group-averaged waveforms and subject-level plots from these data-driven ROIs showed developmental differences that broadly aligned with those observed in the hypothesis-driven analyses at Cz (Supplementary Figs. 12–14). See Supplementary Results, section: Mass-univariate analysis results, for full details.

Discussion

The present study investigated central auditory system maturation using CAEPs in response to low frequency /m/ and high frequency /s/ speech stimuli in individuals 5 to 24 years of age. By examining maturational changes in P1 and N1 amplitude and latency from childhood to adulthood, and their associations with speech reception thresholds (SRTs), we aimed to characterize typical auditory system maturation. In addition, these findings are intended to provide a normative benchmark for analysis of maturation of the auditory system in special populations such as children with hearing loss or with neurodevelopmental delays. We found distinct age- and stimulus-dependent changes in morphology, amplitude, and latency measures of CAEPs. The N1 peak latency was the only neural measure that significantly predicted behavioral performance on the speech understanding task (in the Right and Left conditions, i.e., when interferers were spatially separated from the target), even after accounting for the age of the participant.

Changes in CAEP morphology, topography, and P1–N1 measures across development

Consistent with our hypotheses, grand-average waveforms at Cz for both phonemes showed a developmental shift from a simpler biphasic morphology in younger children to a more mature multiphasic morphology in adults, likely reflecting maturation of thalamo-cortical and cortical pathways[12,17,32]. In line with prior CAEP findings, the waveform in younger children was dominated by a broad P1 with a small or emerging N1, whereas in adults it was characterized by a reduced P1 and clearly defined N1 and P2 peaks[12,24,28,29,31,32].

All four CAEP measures showed robust age-related changes, but with partly distinct trajectories. N1 amplitude showed a nearly linear increase in negativity with age, whereas P1 amplitude and latency, and N1 latency showed clear non-linear age-related decreases, with the steepest changes in early childhood. Maturation estimates suggested relatively earlier stabilization of P1 amplitude and N1 latency during early adolescence, while P1 latency, and especially N1 amplitude, showed more protracted development into adolescence and young adulthood. In summary, these findings support prior reports that P1/N1 maturation follows a prolonged developmental course[12,28–32], likely reflecting ongoing maturational changes in underlying auditory cortical circuitry, including refinement of intra- and interhemispheric connectivity, improvements in synaptic efficacy, and continued myelination[9,32,97–99].

Differences across scalp sites in age-related changes in waveform morphology and P1 and N1 measures, together with developmental shifts in P1 and N1 scalp distribution, indicate that the observed pattern of CAEP maturation varied with recording location[12,24,29,30]. Central and frontal sites appeared more sensitive to age-related changes in P1 and N1 than parietal sites. Notably, the data-driven early ROIs captured maximal age-related effects in frontocentral regions and included Cz for both phonemes. The maturational trends derived from these early ROIs converged with those observed in the hypothesis-driven Cz-based analysis, supporting the robustness of the developmental effects across analytic approaches (See Supplementary Fig. 14).

A key finding was that maturational patterns differed between phonemes. Derivative-based maturity estimates suggested that responses to /s/ may attain adult-like values earlier than responses to /m/ for several CAEP measures. This is consistent with our prediction of distinct maturational trajectories for high- and low-frequency speech sounds. Additionally, across all age groups, N1 amplitude was greater for the low-frequency /m/ than for the high-frequency /s/, and the rate of change with age differed by stimulus, leading to larger between-stimulus differences in N1 amplitude with age. Also, the N1 latency was shorter for /s/ than for /m/ for all groups except the younger children group. In contrast, P1 amplitude differences were limited to the 5–8 years old age group, with lower amplitudes for /m/ than for /s/. These patterns are broadly consistent with adult and infant studies using low- and high-frequency phonemes or tones[20,26,44,100,101]. The larger N1 response to /m/ than to /s/ may partly reflect tonotopic organization in auditory cortex, with low-frequency sounds activating more superficial regions and yielding stronger scalp responses[10,38,44,102]. However, prior adult studies using a broader phoneme set found that not all low-frequency phonemes elicit stronger N1 responses than /s/[44]. Thus, frequency alone is unlikely to fully explain our findings of amplitude differences between /m/ and /s/. Overall, the difference more

likely reflects the combined influence of frequency, spectral-temporal complexity, and phonetic features, as /m/ is a low-frequency, periodic, voiced nasal, whereas /s/ is a high-frequency, aperiodic, voiceless fricative[21,44,103,104].

Stimulus-specific differences were also observed in the grand-average waveform morphology among the younger children. The response to /s/ showed a small emerging N1 notch, whereas /m/ showed a relatively larger N1 notch, despite the overall immature morphology. This difference may partly reflect the finding that the N1 peak was generally larger for /m/ than for /s/ across all age groups. Additionally, there was substantial individual variability in waveform morphology among younger children, with some showing relatively prominent N1 peaks and others showing more immature N1 responses (See Supplementary Fig. 15–18 showing individual waveforms for all participant groups). Such variability in auditory maturation is a hallmark of many developmental studies, suggesting that auditory sensitivity and processing of complex signals may mature at different rates amongst children of the same age[12,17,23,30].

Taken together, these findings support that P1 may primarily reflect early auditory detection, whereas N1 may be a more refined index of auditory cortical processing that is sensitive to the spectral-temporal properties of speech stimuli[10,15,33,101]. More broadly, the present findings highlight the importance of considering scalp location, stimulus characteristics, and individual variability when interpreting CAEP maturation.

Associations between CAEPs and speech reception thresholds

The second aim of this study was to examine how maturational differences in CAEPs, specifically P1 and N1 amplitude and latency, elicited by the onset of low- and high-frequency speech sounds presented in quiet, are related to speech understanding performance in both quiet and noisy listening conditions. We hypothesized that more mature CAEP responses, i.e., lower P1 amplitude, higher N1 amplitude, and shorter P1 and N1 latencies, would be associated with better speech understanding, i.e., lower SRTs[66–68].

This hypothesis was partially supported by our findings. N1 latency for /s/ stimuli emerged as a significant predictor of SRTs, with shorter latencies associated with better speech understanding performance in the Right and Left spatial interferer conditions, but not in the Quiet or Front (co-located interferer) conditions. It is important to note that this association was independent of age. These results suggest that faster low-level auditory processing of high-frequency speech sounds may be associated with better ability to extract speech information in the presence of background interferers that are spatially separated from the target speech. This neural-behavioral association may be consistent with an underlying developmental process regarding how children utilize spatial cues to extract speech information from their environment. Spatial cues generally lead to improved performance relative to the Front condition, but performance in the presence of spatial cues also introduces between-subject variability in SRTs, which may result in the detection of meaningful associations with neural timing. Notably, shorter N1 latency reflects faster neural processing. Prior work suggests that individuals with faster neural timing may have better access to temporal and spectral cues important for speech perception, particularly in conditions where speech and noise are spatially separated[105].

Although N1 latency for /s/ stimuli did show a significant relationship with SRTs, the overall variance explained was modest. Moreover, none of the other CAEP measures were significantly associated with speech understanding. These modest and null associations may be explained, at least in part, by several factors. First, CAEPs were recorded in quiet, whereas the speech perception task involved active word understanding in both quiet and noise conditions. Prior research has shown that onset CAEPs recorded in quiet are only weakly related to speech perception in participants with typical hearing[105–107], whereas stronger associations have been observed when CAEPs are recorded in the presence of noise[58,64]. Second, onset CAEPs were recorded under passive listening conditions and only reflect the early neural encoding of spectro-temporal properties of speech stimuli but behavioral speech understanding, particularly in complex environments, relies on a broader perceptual system that also includes attention, memory, and other cognitive processes. Studies have found that associations between CAEPs and speech perception are stronger when active task paradigms are used, which engage advanced auditory processing with attention or top-down modulation[108,109]. Finally, the stimuli used to elicit CAEPs were isolated phonemes, while the behavioral task required recognition of bisyllabic words. Prior work suggests that neural–behavioral correlations are better when the neural stimuli closely resemble the speech material used in the behavioral test[110].

That said, the finding that N1 latency to /s/ is significantly associated with SRTs on a word recognition task among the typically developing children and adults in our study is promising and suggests potential for clinical applications. This may be especially valuable for populations where reliable behavioral speech testing is difficult, such as very young children, individuals with atypical hearing (e.g., auditory neuropathy), or individuals with cognitive or language challenges, where passively recorded CAEPs might offer an objective marker of cortical auditory processing capacity relevant to speech perception[19,20,111]. However, our current findings are preliminary and warrant future research to validate the association between N1 latency and SRTs. At present, these findings should be interpreted primarily as research evidence of a neural–behavioral association, rather than as demonstrating clinical readiness of N1 latency as a marker.

In summary, our findings suggest that N1 latency for /s/ stimuli may serve as a meaningful neural correlate of speech understanding performance in complex listening environments. However, the variance explained was modest, indicating that multiple other factors, including sensory, cognitive, and attentional processes, may contribute to the overall speech-in-noise understanding performance. While CAEP measures may not fully predict speech-in-noise skills in all listening conditions, they provide insight into the maturational readiness of auditory cortical systems that support successful speech processing.

Broader implications for language development

Speech perception is fundamental to spoken language development. Notably, speech perception and production may mutually influence each other during language acquisition[112]. Speech-evoked event related potentials

(ERPs) and CAEPs provide an objective window into the maturation of cortical mechanisms that support speech perception in children, and prior ERP and CAEP studies suggest that neural responses to speech are associated with language-related developmental outcomes[19,32,112–116]. In the present study, the low-frequency nasal /m/ and high-frequency fricative /s/, which differ in their spectral emphasis, evoked distinct developmental CAEP patterns. These findings suggest that frequency-specific phoneme-evoked CAEPs may be a promising avenue for future studies to examine how maturation of cortical processing contributes to the development of speech perception of sounds with different spectral profiles, and how this, in turn, relates to broader language development.

The relatively earlier maturation of /s/-evoked CAEP indices, compared with the more protracted maturational time course observed for /m/, may reflect earlier maturation of cortical processing for high-frequency fricative information. This possibility is notable because previous work, particularly in pediatric audiology, has shown that children require greater access than adults to high-frequency speech information for the detection and identification of fricatives such as /s/ and /z/, and that these cues are important for morphological and phonological development[67,68,117]. The /s/ phoneme is linguistically important because of its frequent use in word-final position to mark plurality (e.g., words), verb agreement (e.g., she smiles), possessiveness (e.g., person's speech), and contracted forms (e.g., it's late or she's dancing)[67,68]. Consistent with this view, reduced access to high-frequency information in children with hearing loss has been associated with vulnerabilities in the development of fricative production, as well as phonological and morphological development[68,118].

It is therefore plausible that our findings of relatively earlier maturation of /s/-related cortical processing may have broader developmental relevance, and may reflect early refinement of the neural encoding of the aforementioned speech features that are important for language learning in children. However, this interpretation remains speculative because language ability was not directly assessed in the present study. Importantly, the maturational order of the present CAEP measures does not parallel the typical order of consonant acquisition, in which nasals are generally acquired earlier than fricatives[119]. This mismatch is not unexpected, as maturation of cortical responses to speech may not map directly onto the developmental order of speech production, which depends strongly on the motor articulatory apparatus. Future work combining phoneme-evoked CAEPs with language measures will be needed to clarify how these frequency-specific patterns of cortical processing are related to children's language abilities. Moreover, future work will be required to better understand the association with speech production.

Strengths, limitations and future directions

The present study had several strengths. Our participants spanned a wide and continuous age range of typical development, enabling us to capture early non-linearities in auditory maturation tracked by changes in CAEP measures. The use of high-density EEG offered the opportunity to not only examine P1 and N1 peak measures at Cz, but also to characterize developmental changes across additional scalp sites and electrode clusters, and to visualize finer-grained topographical changes in response to the auditory stimuli across age. A key strength of the study is that the primary hypothesis-driven Cz analyses were complemented by broader whole-scalp data-driven analyses. The convergence of age-related patterns across these analyses strengthens confidence in the robustness of the observed developmental effects.

Our task enabled assessment of speech perception in four different listening conditions allowing us to capture neuro-behavioral associations and avoid floor and ceiling effects in task performance. The differential maturation patterns observed for /m/ and /s/ stimuli highlight the importance of frequency-specific speech processing in understanding auditory development. Overall, the study characterized typical auditory maturation, revealed associations with speech understanding, demonstrated the existence of substantial individual variability in development, and charted overall trajectories for the P1 and N1 peak measures. The robust age-related changes in CAEP measures suggest that they can serve as objective neurophysiological indices for assessing auditory maturation and identifying developmental delays in clinical populations.

There are several limitations to consider. First, the study might have been underpowered to detect weaker associations between CAEP measures and speech understanding in the Quiet and Front (co-located interferer) conditions. Second, although speech understanding was measured in both quiet and noise, CAEPs were only assessed in quiet, which limited direct comparison across measures and may partially explain the relatively modest neural-behavioral associations found in our study. Finally, although this study included only typically developing participants, a passive EEG task was used to ensure the paradigm remains applicable for populations that are more difficult to test such as individuals with developmental delays. However, in typically developing individuals, the addition of active EEG tasks might have yielded stronger associations with behavioral performance.

The study underscores the need to explore additional factors that contribute to associations between auditory cortical processing and behavioral measures of speech understanding in challenging environments. Two potential directions are considered relevant for future studies. First, the task used here for behavioral measures of speech understanding was relatively easy, the goal being to benchmark performance across a wide age range. A task that involves more complex speech processing such as understanding sentences would add depth to the topic and provide insight into associations with cortical processing of speech during development. Second, future studies could incorporate speech-in-noise stimuli for cortical potential recordings and employ EEG task designs that include both passive and active paradigms. This would enable the assessment of both lower-level sensory encoding and higher-level speech-related cortical processing involving top-down modulation, helping to disentangle the respective contributions of different levels of auditory processing and cognitive factors to behavioral performance. Considering the substantial individual variability in CAEP measures, particularly in younger children, the normative age-related trajectories reported here should be interpreted as group-level benchmarks, rather than individual-level diagnostic criteria. In heterogeneous clinical populations

(e.g., children with developmental delays), such variability may limit the specificity of single-session CAEP measures as biomarkers, underscoring the value of individual longitudinal profiling alongside group norms. Future longitudinal study designs would provide a more nuanced understanding of individual developmental trajectories and their variability.

Conclusion

Our findings demonstrate significant developmental changes in CAEP waveform morphology, characterize the developmental trajectories of P1 and N1 amplitudes and latencies for both low-frequency /m/ and high-frequency /s/ phonemes, and reveal frequency-specific differences in auditory maturation. We also found evidence of an association between speech-evoked CAEPs and speech understanding performance in noisy listening conditions. This study provides a comprehensive characterization of auditory cortical maturation in response to high- and low-frequency phonemes across a wide developmental age range. The findings highlight the dynamic nature of cortical auditory system maturation and its relevance for speech perception. While these findings do not represent diagnostic thresholds, they offer normative developmental benchmarks for future research on both typical and atypical auditory development.

Data availability

Anonymized data can be made available on request.

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Author contributions
K. A. was involved in experiment design, collected and analyzed data, and wrote the first draft of the manuscript; N. D. D. and S. P. G. were involved in experiment design, and collected data; R. Y. L. conceived of the study and designed experiments, and contributed to data interpretation. C. B. B. contributed to experiment design, data interpretation and manuscript writing. All authors were actively engaged in discussions on the interpretation of the results, provided input on the manuscript, and approved the final version.

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Declarations

Competing interests
The authors declare no competing interests.

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