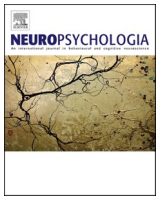
Neuropsychologia 217 (2025) 109219

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia



Changes in auditory evoked responses at different levels of linguistic processing in adults and school-age children: An MEG study

Marco C.H. Lai [a,*], Ellie Abrams [a], Sherine Bou Dargham [b], Jacqui Fallon [c], Ebony Goldman [d], Miriam Hauptman [e], Alicia Parrish [f], Sarah F. Phillips [f,g], Alejandra Reinoso [h], Liina Pylkkänen [a,f]

[a] Department of Psychology, New York University, New York, NY, USA
[b] Institute of Psychiatry, Psychology and Neuroscience, King's College London, London, UK
[c] Department of Psychology and Neuroscience, University of Colorado Boulder, Boulder, USA
[d] Department of Speech-Language-Hearing Sciences, The Graduate Center, City University of New York, New York, NY, USA
[e] Department of Psychological and Brain Sciences, Johns Hopkins University, Baltimore, MD, USA
[f] Department of Linguistics, New York University, New York, NY, USA
[g] Georgetown University Medical Center, Georgetown University, Washington, DC, USA
[h] Department of Communication Sciences and Disorders, Northwestern University, Evanston, IL, USA

ARTICLE INFO

Keywords:
Language development
Sound repetition
Lexicality
Contextual effect
Auditory evoked magnetic fields
MEG

ABSTRACT

While the development of speech processing begins early in life, adult-level language proficiency takes a significant amount of time to emerge. How children comprehend speech with their immature auditory systems and how they gradually achieve adult-like language proficiency remains poorly understood. The present study used magnetoencephalography (MEG) to examine developmental changes during auditory processing of language in school-age children and adults at multiple levels of representation. Twenty-one children (ages 7–15 years) and twenty-five adults (ages 18–40 years) listened to repeated sounds (e.g., "*mmm mmm*"), one-word sounds (e.g., "*mmm glass*"), and adjective-noun phrases (e.g., "*green glass*") and afterwards selected a matching picture at the end of each trial. Our results show that at the basic sound level, both children and adults exhibited adaptation to repeated sounds. At the word level, children's N100m responses to lexicality in the left hemisphere correlated with their age, suggesting an enhancement in the efficiency of phonological processing with increasing age. Finally, at the phrase level, children showed increased N400m responses to words in phrasal contexts than to those without a context in the right temporal lobe. This suggests greater involvement of right hemisphere in children during phrase-level speech comprehension.

1. Introduction

Speech comprehension is a complex process, involving sound detection, word recognition, and integration of multiple words into larger units such as phrases and sentences. Humans are able to complete this process within hundreds of milliseconds, even from a very young age (Kuhl, 2004). However, it takes many years to achieve adult-like language proficiency in processing speech information (McMurray et al., 2022). Neuroimaging studies also provide evidence that the human auditory system does not fully mature until adolescence or early adulthood (Albrecht et al., 2000; Bishop et al., 2007, 2011; Mahajan and McArthur, 2012; Sussman et al., 2008). It remains unclear how children, with their developing auditory systems, comprehend speech information and at what developmental stage they exhibit adult-like brain responses. The current study used magnetoencephalography (MEG) to examine developmental profiles of auditory language processing across multiple levels of linguistic representations in both school-age children and adults.

1.1. Slow-developing process of auditory evoked responses

Previous research utilizing neuroimaging techniques such as electroencephalography (EEG) and MEG has demonstrated differences in brain responses to auditory stimulation between adults and children (Albrecht et al., 2000; Bishop et al., 2007, 2011; Mahajan and McArthur, 2012; Paetau et al., 1995; Pang and Taylor, 2000; Ponton et al., 2000,

* Corresponding author. Department of Psychology New York University 6 Washington Pl. New York, 10003, NY, USA.
E-mail address: marco.chiaholai@nyu.edu (M.C.H. Lai).

https://doi.org/10.1016/j.neuropsychologia.2025.109219
Received 10 September 2024; Received in revised form 11 February 2025; Accepted 12 July 2025
Available online 14 July 2025

2002; Sussman et al., 2008; Wunderlich and Cone-Wesson, 2006). Specifically, compared to adults' typical P100 (or P50)-N100-P200 auditory complex, children's most prominent auditory components are the P100 and N200/N250 responses. It has been shown that the amplitudes and latencies of these two components decrease with age, whereas the N100 component gradually emerges during children's development. Studies have indicated that the adult-like N100-P200 complex induced by speech stimuli may not be reliably identified until the age of 10 (Shibasaki and Miyazaki, 1992). Previous research has also indicated that most of the early auditory components (e.g., the P100 (or P50)-N100-P200 complex in adults and the P100 and N200/N250 in children) are associated with perceptual processing of auditory information. Additionally, word-level and sentence-level information are usually represented in later time windows, such as N400 component. We have reviewed the relevant auditory components in response to different levels of linguistic processing in Table 1.

1.2. Experience-related neural changes in language learning

The early evoked responses, such as the N100-P200 complex, are often used as an indicator of human auditory processing or speech perception due to their sensitivity to the temporal and physical characteristics of auditory stimuli (Näätänen and Picton, 1987). Previous studies have indicated that this sensitivity to auditory stimulation is influenced by experience. For instance, Tremblay et al. (2009) found that, after six sessions of training (one session per day) in syllabic sound discrimination, adults showed an amplitude enhancement of the P200 component. Similarly, Brem et al. (2010) observed that, after an 8-week training in grapheme-phoneme correspondence, young children showed increased N100 responses, suggesting a role for early evoked responses in phonological decoding and grapheme-phoneme mapping during early development. Additionally, research has found similar learning-induced neural changes in the study of reading acquisition. Using functional magnetic resonance imaging (fMRI), Monzalvo and Dehaene-Lambertz (2013) examined the effects of reading acquisition on children's spoken language processing by comparing activation differences between 6-year-old (beginning readers) and 9-year-old (advanced readers) children during sentence listening. Their findings revealed that, when listening to the sentences in their native language, 9-year-olds exhibited increased activation in the visual word form area (VWFA) compared to 6-year-olds, suggesting that greater reading experience reshapes the spoken language network by recruiting visual regions responsible for orthographic codes (Yoncheva et al., 2010).

1.3. The present study

The present study aims to examine how children's spoken language network changes with increasing language experience, as operationalized by age (Monzalvo and Dehaene-Lambertz, 2013). Research has demonstrated that the auditory system and spoken word recognition undergo a prolonged developmental trajectory from early childhood through adolescence (Litovsky, 2015; McMurray et al., 2022; Moore and Linthicum, 2007). These findings motivated the current study to investigate age-related changes in auditory processing throughout children's development (ages 7–15 years in this study). Previous research on auditory development has primarily focused on individual level of processing, such as sound perception, word recognition, or sentence comprehension (see the summary in Table 1). Few studies have systematically examined developmental changes in language processing at multiple levels (but see Kolozsvári et al. (2021)). Additionally, the developmental profile of children's N100 response is less characterized due to its slow maturation and temporal overlap with other dominant auditory components, such as P100 and N200/N250. In the current study, we employed a recently developed data-driven approach to identify components in the sequence of auditory evoked responses (Bruzzone et al., 2021; Haumann et al., 2020) and examined children's and adults' auditory components in response to sound-, word-, and phrase-level information. Furthermore, previous studies investigating hemispheric differences in language processing have yielded mixed results during children's development (Berl et al., 2014; Holland et al., 2007; Kadis et al., 2011; Olulade et al., 2020; Szaflarski et al., 2006a,b; Weiss-Croft and Baldeweg, 2015). Therefore, we also investigated the developmental trajectories of hemispheric asymmetries at different levels of linguistic processing in children. Previous studies have indicated that the neural generators of auditory components observed at similar time latencies (e.g., N100) may not be identical between children and adults (Pang and Taylor, 2000; Takeshita et al., 2002). Under this assumption of developmental differences in auditory components, all of our analyses were conducted separately for each group, with no direct comparisons between children and adults.

2. Methods

2.1. Participants

Twenty-one children (11 females, mean age: 9.9 years, range: 7–15 years) and twenty-five adults (19 females, mean age: 22.0 years, range: 18–40 years) participated in the study. Participants were recruited from the New York metropolitan area. They were all English native speakers with normal hearing and vision (or corrected-to-normal vision) and had no history of neurological or developmental disorders. Except for one left-handed adult, all participants were right-handed. A written informed consent was obtained from all adult participants and the parents of all child participants, and compensation was provided for their participation. The study was approved by the New York University Institutional Review Board and all the methods were performed in accordance with relevant guidelines and regulations.

2.2. Stimuli and experimental design

The present study used the dataset from one of the four-task protocol of the NYU Kid-Lang project (https://wp.nyu.edu/neurolinglab/for-parents/). The comprehension task consists of three conditions: phrase, one-word, and baseline. In the phrase condition, 36 adjective-noun phrases were formed using 6 color adjectives ("*black*", "*blue*", "*green*", "*pink*", "*red*", "*white*") and 6 object nouns ("*comb*", "*door*", "*glass*", "*heart*", "*house*", "*sword*"). In the one-word condition, the color adjectives were replaced with a "*mmm*" sound. The goal of using this "*mmm*" sound was to provide a natural sound arising from the human vocal tract without initiating lexical access. In the baseline condition, the "*mmm*" sound was presented twice (e.g., "*mmm mmm*"). The sound files, recorded by a native English speaker, ranged in length from 446 to 615 ms.

In the experiment, all trials from the three conditions (50 trials each) were presented in a random order. Each trial began with a fixation cross shown at the center of the screen for 600 ms, followed by a 300-ms blank screen. Subsequently, two auditory stimuli were presented consecutively, followed by a 600-ms blank screen. Each auditory stimulus maintained a consistent duration of 875 ms (Fig. 1). In the phrase and one-word conditions, participants viewed 8 object pictures at the end of each trial and were asked to select the picture that matched the auditory stimuli they heard via a button press.

2.3. Data acquisition and preprocessing

Continuous MEG data were acquired using 157-channel axial gradiometer systems (Kanazawa Institute of Technology, Kanazawa, Japan), with a sampling rate of 1,000 Hz and an online low-pass filter of 200 Hz. Before the MEG recording, participants' headshapes were digitized using a FastSCAN laser scanner (Polhemus, VT, USA) for later coregistration. Five marker coils were used to localize participants' heads relative to the MEG sensors. Marker measurements were obtained before and after the experiment.

Table 1
A summary of sensor-level auditory evoked potentials/fields in typically developing school-age children and adults.

Study	Method	Paradigm/Stimuli	Task	Native Language	Group	Age	N	Target Component/ Reported or Selected Time Window	Main Findings of Sensor-Level Auditory Evoked Responses	Other Findings
Sound repetition										
Karhu et al. (1997)	EEG	• MMN paradigm • Stimuli: simple tones	Passive listening (unattended) while watching a silent video	N/A	Child	9	42	N100: 124-130 ms (vertex); 167 ms (temporal) N200: 274 ms (vertex)	[repeated tones] • N100: decreased amplitude • N200: increased amplitude	N/A
					Adult	23-49	16	N100: 107-113 ms (vertex)	[repeated tones] • N100: decreased amplitude	N/A
Ruhnau et al. (2011)	EEG & MEG	• Two conditions presented in separate blocks - repetitive tones - random tones	Passive listening (unattended) while watching a silent video	N/A	Child	9-10	15	P100(m): 75-105 ms N100(m): 90-130 ms N200(m): 200-240 ms	[repeated tones vs. random tones] • (MEG) P100m & N200m: no difference • (EEG) P100: no difference • (EEG) N100: decreased amplitude • (EEG) N200: increased amplitude	[repeated tones vs. random tones] (source ROI analysis) • ROI: bilateral PAC and middle STG • (MEG) N100m: decreased amplitude
					Adult	24-34	20	P100(m): 50-80 ms N100(m): 90-130 ms	[repeated tones vs. random tones] • (MEG) P100m: no difference • (EEG) P100: increased amplitude • (EEG & MEG) N100(m): decreased amplitude	[repeated tones vs. random tones] (source ROI analysis) • ROI: bilateral PAC and middle STG • (MEG) N100m: no difference
Muenssinger et al. (2013)	MEG	• MMN paradigm • Stimuli: simple tones	Passive listening (unattended) while watching a silent video	N/A	Child	9-11	22	M100: 80-140 ms	[repeated tones] • M100: no difference	N/A
					Adult	24-35	14	M100: 80-140 ms	[repeated tones] • M100: decreased amplitude	N/A
Lexicality effect										
MacGregor et al. (2012)	MEG	• Stimuli: - words - pseudowords	Passive listening (unattended) while watching a silent video	English	Adult	18-35	22	Early time window: 50-80 ms Middle time window: 110-170 ms Late time window: 320-520 ms	[words vs. pseudowords] • All time windows: increased amplitude	[words vs. pseudowords] (source analysis) • Early time window: increased amplitude in the bilateral temporal lobes and the left pre-/post-central cortex • Middle time window: increased amplitude in the right temporal lobe • Late time window: increased amplitude in the left IFG, left STG, and the right ATL
Cheng et al. (2014)	EEG	• Repetition paradigm • Stimuli: - words - pseudowords - nonwords	Indicating whether all three items in each trial were the same	English	Adult	18-28	24	P200: 200-300 ms N400: 400-600 ms	[first item in each trial] • Left-frontal P200 amplitude: words ≈ pseudowords < nonwords • Left hemisphere N400 amplitude: words > pseudowords ≈ nonwords	N/A
Caffarra et al. (2017)	MEG	• Stimuli: - words - scramble sounds	One-back task: pressing a button when the current stimulus was identical to the previous one	Basque-Spanish	Child	4-8	30	Early time window: 0-200 ms Late time window: 300-700 ms	[words vs. scramble sounds] • Early time window: decreased amplitude • Late time window: increased amplitude	N/A
Phrase- & Sentence-level processing										

(*continued on next page*)

Table 1 (*continued*)

Study	Method	Paradigm/Stimuli	Task	Native Language	Group	Age	N	Target Component/ Reported or Selected Time Window	Main Findings of Sensor-Level Auditory Evoked Responses	Other Findings
Holcomb et al. (1992)	EEG	• Conditions: - best completions (grammatical sentences) - anomalous completions (semantic violations)	Indicating whether the sentence made sense	English	Child & Adult	5-26(split into ten age groups)	130	P50: 0-100 ms N100: 90-200 ms P250: 200-500 ms N400: 300-500 ms Late N400: 500-800 ms	[anomalous vs. best completions] • N400 & Late N400: amplitude differences reduced with age	N/A
Hahne et al. (2004)	EEG	• Conditions: - grammatical sentences - semantic violation sentences - syntactic violation sentences - fillers	Grammaticality judgment	German	Child	Five age groups: 6, 7, 8, 10, 13	102	Early time window: 100-300 ms Middle time window: 400-600 ms Late time window: 600-1500 ms	[syntactic violations vs. grammatical] • Early time window: 13-year-olds showed greater negativity; 6-year-olds showed greater positivity. • Children between 7-13 showed biphasic responses (middle time window: greater negativity; late time window: greater positivity). • 6-year-olds showed a late positivity between 1250-1500 ms.	N/A
Hasting & Kotz (2008) Experiment 1	EEG	• Conditions: - subject-verb agreement violation phrases - word category violation phrases	Grammaticality judgment	German	Adult	20-29	24	Early time window: 100-300 ms Late time window: 300-800 ms	[ungrammatical vs. grammatical] • Early time window: greater negativity to both violations • Late time window: greater positivity to subject-verb agreement violations only	N/A
Segaert et al. (2018)	EEG	• Conditions: - minimal phrases (a pronouns & a pseudoverb) - wordlist (two pseudoverbs) - fillers	Detecting reversed speech in the fillers	Dutch	Adult	21 (mean age)	20	P600: 500-700 ms	[minimal phrases vs. wordlists] • P600: no difference	[minimal phrases vs. wordlists] (TFR analysis) • Target words: pseudoverbs at the second word position • Preceding the target word: increased power in the alpha (8-12 Hz) and beta (15-20 Hz) frequency bands • Following the target word: increased power in the alpha (8-12 Hz) frequency band
Dube et al. (2019)	EEG	• Conditions: - subject-verb agreement violation sentences - fillers	Detecting target words in the fillers	English	Child	9-11	24	Time window: 180-380 ms	[ungrammatical vs. grammatical] • Greater negativity at the anterior-central sites	N/A

N/A: not addressed or not reported in the study. N: number of participants for data analysis. For the columns of main findings and other findings, texts in square brackets indicate the contrast or condition. ROI: region of interest. PAC: primary auditory cortex. STG: superior temporal gyrus. IFG: inferior frontal gyrus. ATL: anterior temporal lobe. TFR: time-frequency representation.

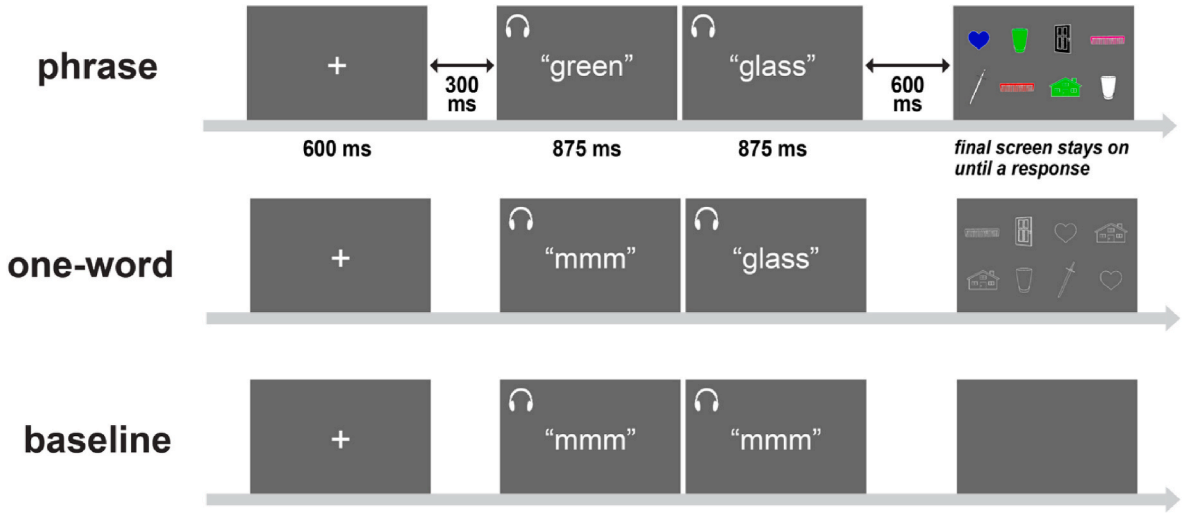


Fig. 1. Trial structure of each condition in the comprehension task.

The raw MEG data underwent noise reduction using the Continuously Adjusted Least Squares Method (CALM62; MEG160 software v2.004A–Yokogawa Electric Corporation and Eagle Technology Corporation, Tokyo, Japan). MNE-Python (v0.23; Gramfort, 2013) was used for data preprocessing and statistical analyses. The noise-reduced data were band-pass-filtered between 1 and 40 Hz. Bad sensors were identified by visual inspection and interpolated using the remaining sensors. An independent component analysis (ICA) algorithm was applied to detect and remove artifacts such as eyeblinks, heartbeats, and external noise. The continuous data were then segmented into epochs time-locked to event onsets (the onset of the first auditory stimulus in each trial), with a time range of −100 ms–1,750 ms relative to the event onset. All the epochs were then baseline-corrected using the 100 ms time window prior to the event onsets. For epoch rejection, the artifact detection method from MNE-Python with a threshold of 3,000 fT and visual inspection were both used to reject noisy epochs. The mean artifact rejection rates were 10.9 % in adults and 17.6 % in children. The remaining epochs were equalized across three conditions and averaged to obtain the evoked responses for each condition.

As individual MRI structural images were not collected in the present study, for the child group, we used an MRI template (4.5–18.5 years old atlas) from the NIHPD database (Fonov et al., 2011; https://www.mcgill.ca/bic/software/tools-data-analysis/anatomical-mri/atlases/nihpd) for source-level analysis. For the adult group, the FreeSurfer average brain was used as their template. First, each participant's digitized headshape was coregistered to the template corresponding to their age group. A source space was then constructed with an "*ico4*" resolution, consisting of 2,562 vertices in each hemisphere. A forward solution from vertices was computed using the boundary element model. The channel noise covariance matrix was estimated using the 100-ms baseline period prior to the event onset and regularized by the automatic method (Engemann and Gramfort, 2015). With the forward solution and the noise covariance matrix, an inverse solution was computed with "*free*" orientation and applied to the evoked responses to yield dynamic statistical parametric maps (dSPM) (Dale et al., 2000) for each condition. Finally, the estimated source activity was morphed to the NIHPD MRI template and the FreeSurfer average brain template for children and adults, respectively.

2.4. Statistical analyses of MEG data

The following section summarizes the data analysis pipeline used in the present study. First, a data-driven approach was used to identify components of interest and estimate peak latencies for each participant in each condition. At the sensor level, group-level statistical analyses were conducted on the mean amplitudes of the components using the lme4 (v1.1.25; Bates et al., 2015) and lmerTest (v3.1.3; Kuznetsova et al., 2017) packages in R (v4.0.2; R Core Team, 2020). At the source level, we used a spatial clustering permutation test to localize the effects of interest. Furthermore, within the child group, we investigated the correlation between age and their brain responses.

In a review paper, Moore and Linthicum (2007) indicated that the auditory cortex undergoes layer-by-layer maturation from age 5 to 12. It is not until age 11 or 12 that children achieve a similar axon density to adults. Due to the intrinsic differences in the auditory system between children and adults, there is uncertainty in stating that the auditory components with the same labels (e.g., N100m and N400m) in both groups have similar underlying neural generators (Pang and Taylor, 2000; Takeshita et al., 2002). Therefore, all analyses were conducted separately for the two groups.

2.4.1. Individual-level analysis: identifying components of auditory evoked fields

First, we used the "*ft_megrealign*" function from the FieldTrip toolbox (v20201128; Oostenveld et al., 2011) to realign individual data to the averaged sensor locations, by averaging the sensor locations across participants in each age group, for children and adults, respectively. Next, to identify components of interest, we selected 114 sensors (57 sensors in each hemisphere) over the temporal regions as sensors of interest (see the sensor layout in Fig. 2). Based on previous studies, restricting sensors to the temporal regions can better characterize the activity of auditory-evoked responses, enabling a further comparison of hemispheric differences in peak latency and amplitude (Howard and Poeppel, 2009; Parviainen et al., 2019; van Bijnen et al., 2019)

To objectively estimate the peak latency from the sequence of auditory components, we used the Spike-density Component Analysis (SCA) method (Bruzzone et al., 2021; Haumann et al., 2020; https://github.com/nielsthaumann/sca) in the present study. The SCA method is a MATLAB script based on the FieldTrip toolbox and has been shown to effectively differentiate overlapping components in children (Bruzzone et al., 2021). There are three steps in this approach.

(1) Spike-density Component Analysis (SCA): The SCA method was applied to each participant's brain responses in each condition during the time course of the first (0–875 ms) and the second auditory stimulus (875–1750 ms), respectively. First, for each hemisphere, the method identified the peak with the highest amplitude across channels and fitted it to a Gaussian model. Next,

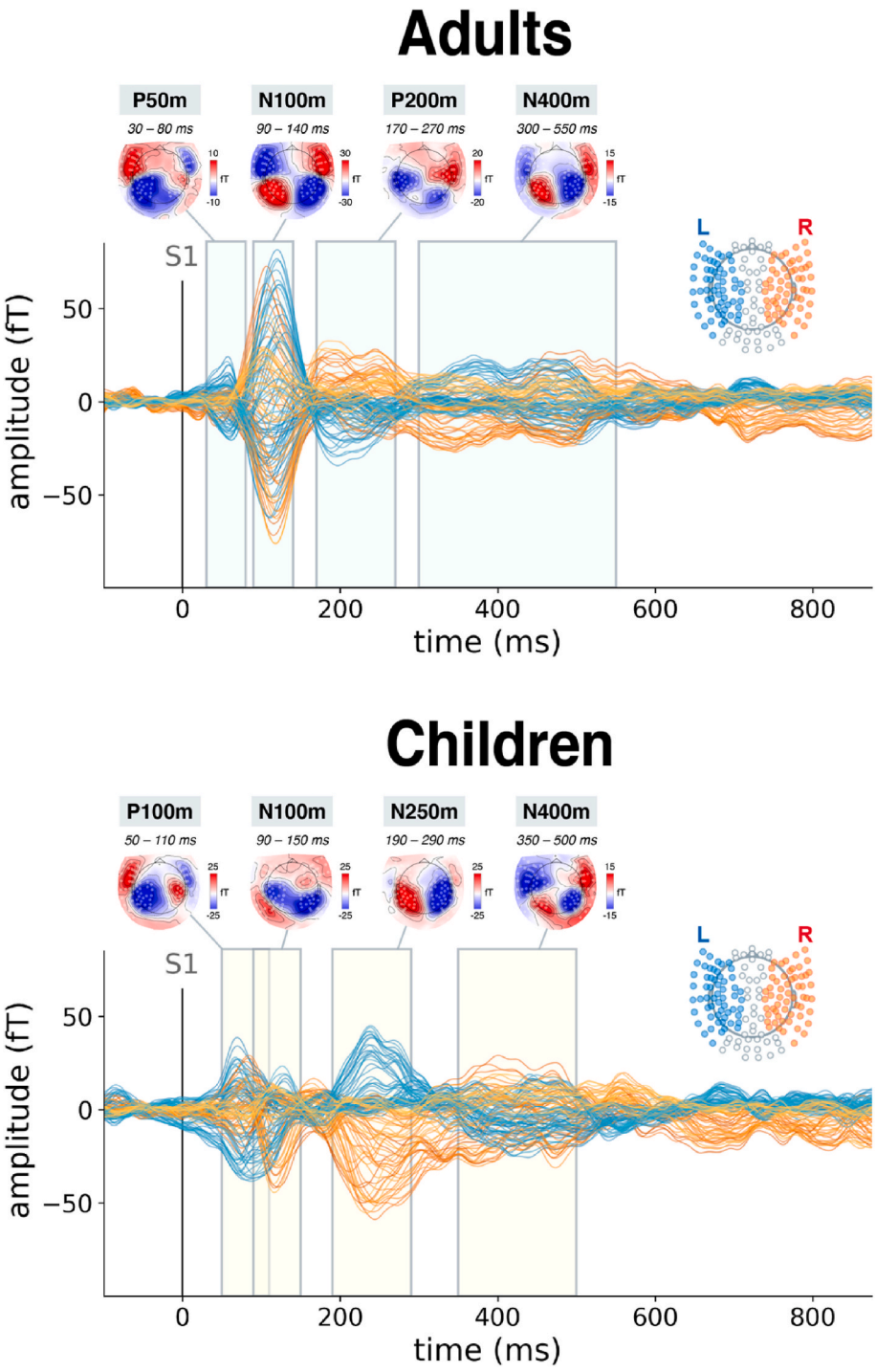


Fig. 2. Auditory evoked fields in adults and children. The grand-average auditory evoked fields time-locked to the first auditory stimuli (S1) across all conditions in adults (upper panel) and children (lower panel). The sensors of interest in the left and right hemispheres and the corresponding evoked responses are indicated by blue and orange, respectively. In each group, time windows of components of interest are highlighted by rectangles, with topographies of mean magnetic fields shown above.

a component weighting matrix was estimated using linear regression and multiplied by the channel weight vector. The component's waveform was then subtracted from the multi-channel waveforms, and its explained variances were estimated. This procedure was repeated until the cumulative explained variances reached the threshold of 95 % variances. The original waveform was then decomposed into overlapping Gaussian-shaped components with distinct spatial topography and temporal information.

(2) *Half-Split Average (HSA) analysis*: The HAS method was used to estimate the consistency of the decomposed Gaussian-shaped component from the previous step. To enhance the accuracy of consistency estimation, the analysis was constrained by the time

windows and polarities (dipole orientations) of the auditory evoked responses[1] (see Fig. 2). Within each time window of auditory evoked responses, the reliability of the decomposed Gaussian-shaped component was evaluated by the HSA method. In this approach, except the tested component, all the other components were subtracted from the HSA. The HSA was then transformed into component space, and its consistency was estimated using Pearson correlation. This procedure was repeated over 1,000 times, and components were considered highly consistent if they appeared in 70 % of the HSAs. These highly consistent components were then used to reconstruct the waveform.

(3) *Peak latency estimation*: The Root-Mean-Square (RMS) values at each time point were calculated for each hemisphere and each condition. We then estimated peak latency based on the highest RMS value within each auditory component's time window. (subjects' peak latencies and RMS mean amplitudes were listed in the Supplementary, Tables S1–S4).

2.4.2. Statistical analysis at the sensor level

At the individual level, for each condition and each hemisphere, we first estimated a participant's RMS values across the sensors of interest at each time point. Then, we averaged the RMS values within a 25-ms time window centered at each component's peak latency as the estimation of mean amplitude. The components of interest listed in Table 2 were determined based on the studies reviewed in Table 1. For each group, participants' RMS mean amplitudes of component of interest were fitted using the lmer model: *Amplitude* ~ *Condition* × *Hemisphere* + *(1* + *Condition* + *Hemisphere* | *Subject)*. In the model, Condition, Hemisphere (left vs. right) and their interaction were treated as fixed factors. By-participant random intercepts and by-participant random slopes for the Condition and Hemisphere were included in the model. The model's parameters were estimated using Maximum Likelihood with the Satterthwaite's approximation (Satterthwaite, 1941) for computing degrees of freedom. To assess the significance of main effects and interactions, likelihood-ratio tests were conducted by comparing a full model with a reduced model.

Table 2
Planned contrasts and components of interest at three levels of linguistic processing.

Level	Effect	Contrast	Components of interest
Sound	Repetition	2nd "*mmm*" (baseline) vs. 1st "*mmm*" (baseline)	Adult: P50m, N100m, P200m Child: P100m, N100m, N250m
Word	Lexicality	adjective (phrase) vs. "*mmm*" (one-word)	Adult: N100m, P200m, N400m Child: N100m, N250m, N400m
Phrase	Contextual effect	noun (phrase) vs. noun (one-word)	Adult: P200m, N400m Child: N250m, N400m

Note: for each contrast, the second level was treated as a reference level in the lmer model.

[1] To determine the time windows of auditory components, the grand-average evoked fields time-locked to the first auditory stimuli were computed by averaging all trials across conditions and participants within each group (Fig. 2). Through visual inspection, four auditory components were identified for the adult group: P50m (30–80 ms), N100m (90–140 ms), P200m (170–270 ms), and N400m (300–550 ms). Similarly, four auditory components were identified for the child group: P100m (50–100 ms), N100m (90–150 ms), N250m (190–290 ms), and N400m (350–500 ms). The same time windows of the components of interest were applied to the responses elicited by the second auditory stimuli.

2.4.3. Statistical analysis at the source level

Similar to the sensor-level analysis, we first estimated the averaged dSPM values for each auditory component. The estimation was performed for each vertex within a 25-ms time window centered at the peak latency of each auditory component for each hemisphere. Subsequently, we conducted a spatial clustering permutation test for the planned contrasts with 10,000 permutations (Maris and Oostenveld, 2007) and used the threshold-free cluster enhancement (TFCE) approach (Smith and Nichols, 2009). Due to the low sensitivity of MEG to deeper sources, the medial walls—the corpus callosum as defined by the Desikan-Killiany atlas (Desikan et al., 2006)—of both hemispheres were excluded from the analyses (Larson et al., 2014). The brain regions reported in the source-level results met the threshold of p(TFCE) < 0.05 and were corrected for multiple comparisons, accounting for the number of components in each planned contrast, using the false discovery rate (FDR) method (Benjamini and Hochberg, 1995).

2.4.4. Examination of age-related changes within the child group

We examined the relationship between the effects of interest and children's age through regression analyses at both the sensor and source levels. The RMS values for each hemisphere at the sensor level and the dSPM values for each vertex at the source level were used in the regression analyses. In the regression model, we fitted the amplitude differences for each contrast against children's age. We then employed a bootstrapping method to validate the age correlation by resampling the data with replacement (Pernet et al., 2011). This procedure was carried out over 10,000 iterations, and the resulting distribution was used to estimate the adjusted p-values for each hemisphere or vertex. All the adjusted p-values reported in the results were corrected for the multiple comparison using the FDR method.

3. Results

3.1. Behavioral results

Data from two children were missing due to a facility problem during the experiment. The remaining data from 25 adults and 19 children were used for the following behavioral analyses. All analyses were conducted using the lme4 (v1.1.25) and lmerTest (v3.1.3) packages in R. For both reaction time and accuracy, Group (Adults vs. Children), Condition (noun vs. phrase) and their interactions were treated as fixed factors in the models. The first level of each factor listed above was set as reference level. By-participant and by-item random intercepts, along with by-participant random slopes for the effects of Condition, were included in the models.

Both groups showed high accuracy on the task. In adults, the accuracies (mean ± SD) for the phrase and one-word conditions were 96.6 ± 3.8 % and 97.2 ± 2.9 %. In children, the accuracies for the phrase and one-word conditions were 88.5 ± 10.2 % and 89.8 ± 9.2 %. The data were analyzed using the glmer model: *Accuracy* ~ *Group* × *Condition* + *(1* + *Condition* | *Participant)* + *(1* | *Item)*. The results revealed a significant main effect of Group [$\beta_{child} = -1.44$, $\chi^2(1) = 19.06$, $p < .001$], indicating that adults had higher accuracy than children.

In adults, the reaction time (mean ± SD) for the phrase and one-word conditions were 1880.2 ± 525.7ms and 1962.8 ± 491.3ms. In children, the reaction time for the phrase and one-word conditions were 3146.0 ± 1091.7ms and 3442.7 ± 1547.1ms. The data were analyzed using the lmer model: log*(Reaction Time)* ~ *Group* × *Condition* + *(1* + *Condition* | *Participant)* + *(1* | *Item)*. The results showed a significant main effect of Group [$\beta_{child} = 0.105$, $\chi^2(1) = 27.46$, $p < .001$], indicating that adults made faster responses than children. Moreover, the reaction times in the phrase condition were faster than in the one-word condition [$\beta_{phrase} = -0.011$, $\chi^2(1) = 4.27$, $p = .039$]. However, no interaction of Group and

Condition was observed [$\beta_{child:phrase} = -0.001$, $\chi^2(1) = 0.08$, $p = .780$].

3.2. MEG results

In the following section, we present our findings on sound repetition, lexicality effect, and phrase-level contextual effect, respectively. For each effect, we first report the results for the adult group at both sensor and source levels. Next, we report the results for the child group at both levels and the correlation between children's age and their brain responses. The summary of the lmer models for all sensor-level results can be found in the supplementary materials (Table S5–S7).

3.2.1. Sound repetition effect in adults: repetition suppression in the early auditory components

At the sensor level, neither a main effect nor an interaction was found for the P50m [$ps > 0.1$, FDR-corrected]. There were significant main effects of the Order of "*mmm*" sounds for the N100m [$\beta_{S2} = -8.43$, $\chi^2(1) = 23.11$, $p < .001$, FDR-corrected] and P200m [$\beta_{S2} = -2.90$, $\chi^2(1) = 14.59$, $p < .001$, FDR-corrected], with a reduction in amplitude for the second "*mmm*" sound compared to the first "*mmm*" sound across both hemispheres in adults (Fig. 3). No main effect of Hemisphere or interaction between Order and Hemisphere was found for the N100m [$\beta_{LH} = 1.03$, $\chi^2(1) = 0.29$, $p = .898$, FDR-corrected; $\beta_{S2:LH} = -0.88$, $\chi^2(1) = 0.80$, $p = .370$, FDR-corrected] or P200m [$\beta_{LH} = -0.14$, $\chi^2(1) = 0.02$, $p = .898$, FDR-corrected; $\beta_{S2:LH} = -0.61$, $\chi^2(1) = 0.82$, $p = .370$, FDR-corrected].

At the source level, spatial clustering permutation tests revealed a significant amplitude reduction in response to the repeated "*mmm*" sound for both N100m and P200m components. For the N100m, an amplitude reduction to repeated sounds was observed in both hemispheres [$p_{tfce} < 0.05$, FDR-corrected; left hemisphere: 1718 vertices, right hemisphere: 1487 vertices]. For the P200m, an amplitude reduction to repeated sounds was found in the left hemisphere, including frontal and anterior temporal lobes as well as cingulate cortex and precuneus [$p_{tfce} < 0.05$, FDR-corrected; 867 vertices].

3.2.2. Sound repetition effect in children: sensor-level repetition suppression in the N100m

At the sensor level, a main effect of the Order of "*mmm*" sounds was observed for the N100m [$\beta_{S2} = -5.66$, $\chi^2(1) = 9.72$, $p = .006$, FDR-corrected], indicating repetition suppression in children's brain responses when contrasting the second "*mmm*" sound with the first "*mmm*" sound. No main effect of Hemisphere or interaction between Order and Hemisphere was found for the N100m [$\beta_{LH} = 1.03$, $\chi^2(1) = 0.16$, $p = .691$, FDR-corrected; $\beta_{S2:LH} = 0.02$, $\chi^2(1) = 0.0002$, $p = .988$, FDR-corrected]. Additionally, we didn't find any main effect or interaction for the P100m [$ps > 0.1$, FDR-corrected] or the N250m [$ps > 0.1$, FDR-corrected].

At the source level, no significant differences to repeated sounds were found. A regression model was further used to examine the relationship between the N100m repetition effect and children's age. A negative age correlation was found in the right-hemisphere sensors [$\beta = -3.50$, $t = -2.44$, uncorrected $p = .024$] but not in the left-hemisphere sensors [$\beta = -1.70$, $t = -0.88$, uncorrected $p = .390$]. However, the age trend in the right hemisphere did not persist after employing the bootstrapping method [adjusted $p = .989$, FDR-corrected].

3.2.3. Lexicality effect in adults: increased P200m responses to spoken words

At the sensor level, a main effect of Condition was observed for the P200m [$\beta_{word} = 4.67$, $\chi^2(1) = 8.45$, $p = .012$, FDR-corrected], indicating that responses to spoken words (e.g., "*green*") were greater than those to "*mmm*" sounds in adults (Fig. 4a). Furthermore, a main effect of Hemisphere was observed for the P200m [$\beta_{LH} = -3.24$, $\chi^2(1) = 8.45$, $p = .012$, FDR-corrected], suggesting that the amplitude was higher in the right hemisphere compared to the left hemisphere. No interaction between Condition and Hemisphere was found for the P200m [$\beta_{word:LH} = -0.61$, $\chi^2(1) = 0.40$, $p = .789$, FDR-corrected]. Additionally, neither a

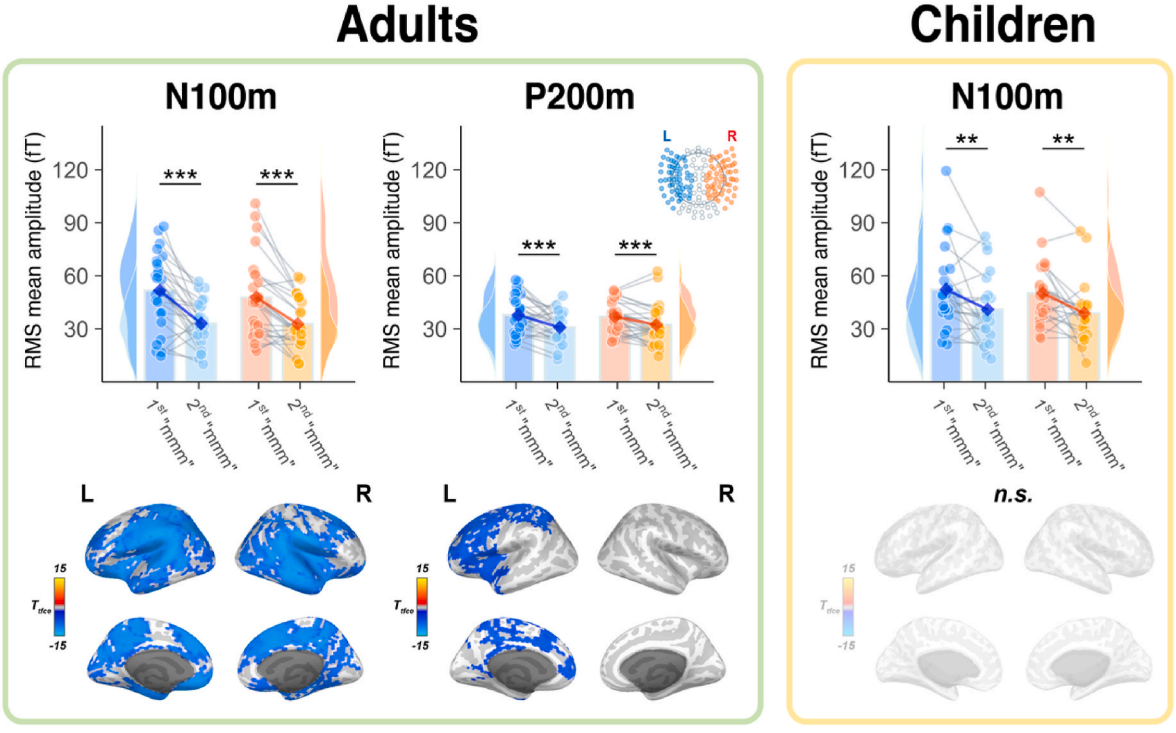


Fig. 3. Sound repetition effect in adults and children. Left panel: RMS mean amplitudes of N100m and P200m, along with corresponding source localization, in the adult group. Right panel: RMS mean amplitudes of N100m in the child group. The sensors of interest in the left and right hemispheres and the corresponding RMS mean amplitudes are indicated by blue and orange, respectively. Significant levels for sensor-level results are denoted by asterisks (*$p < .05$, **$p < .01$, ***$p < .001$; FDR-corrected). Source-level results were set at the FDR-corrected threshold of p (TFCE) < 0.05. L: left; R: right; n.s.: not significant.

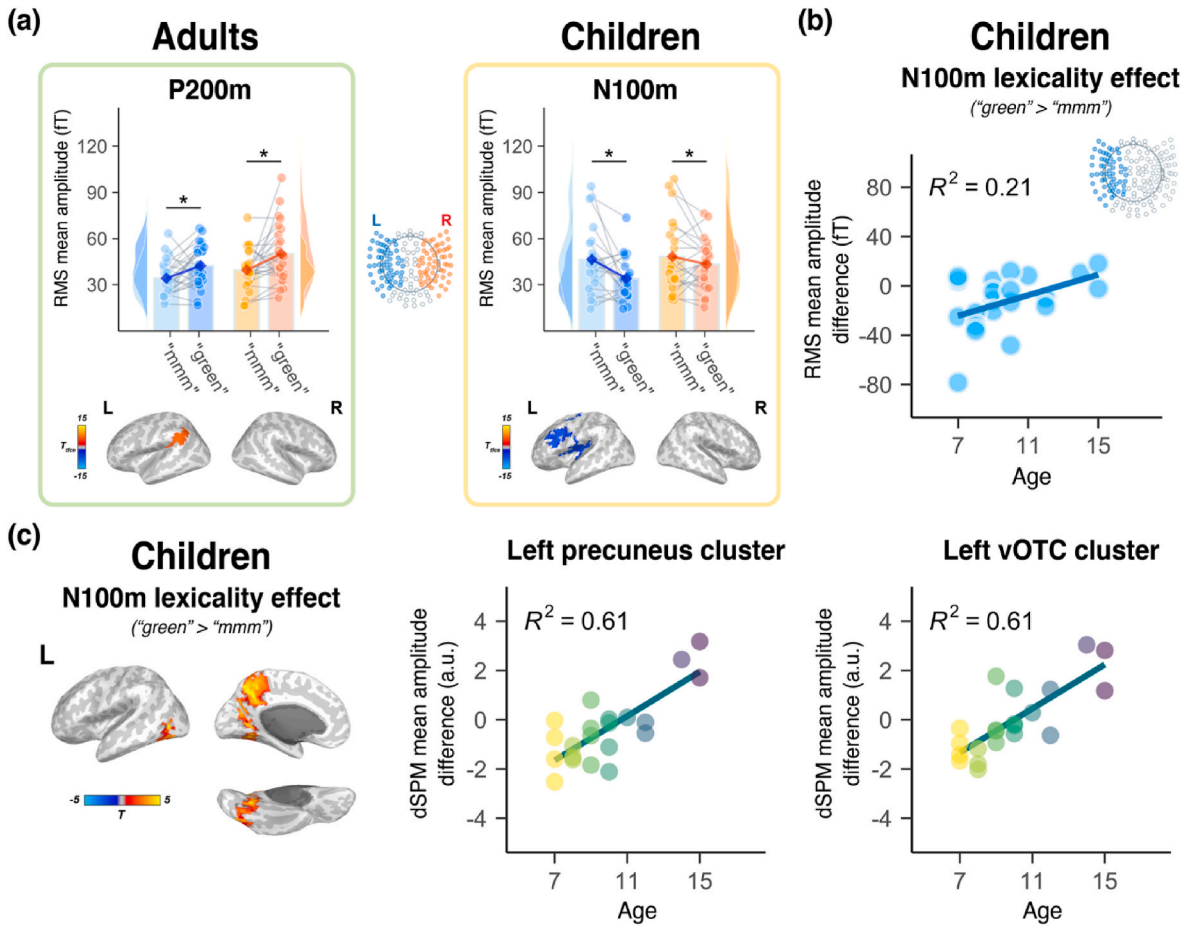


Fig. 4. Lexicality effect in adults and children. (a) Left panel: RMS mean amplitudes of P200m and corresponding source localization in the adult group. Right panel: RMS mean amplitudes of N100m and corresponding source localization in the child group. The sensors of interest in the left and right hemispheres and the corresponding RMS mean amplitudes are indicated by blue and orange, respectively. Significant levels for sensor-level results are denoted by asterisks (*$p < .05$, **$p < .01$, ***$p < .001$; FDR-corrected). Source-level results were set at the FDR-corrected threshold of p (TFCE) < 0.05. (b) Correlation between children's age and N100m lexicality effect in the left-hemisphere sensors. (c) Left panel: significant clusters from the whole-brain regression analysis on the association between children's age and their N100m lexicality effect (adjusted $p < .05$, FDR-corrected). Middle and right panels: scatter plots for visualizing the correlation between children's age and the N100m lexicality effect in the left precuneus cluster and the left ventral occipitotemporal cortex (vOTC) cluster. L: left; R: right.

main effect nor an interaction was found for the N100m [$ps > 0.7$, FDR-corrected] or the N400m [$ps > 0.3$, FDR-corrected].

At the source level, greater amplitudes to words compared to "*mmm*" sounds were observed in the left supramarginal gyrus (SMG) [$p_{tfce} <$ 0.05, FDR-corrected; 47 vertices].

3.2.4. *Lexicality effect in children: left-hemisphere N100m lexicality effect correlated with children's age*

At the sensor level, a main effect of Condition was observed for the N100m [$\beta_{word} = -4.34$, $\chi^2(1) = 5.80$, $p = .048$, FDR-corrected], indicating that responses to spoken words (e.g., "*green*") were lower than those to "*mmm*" sounds in children (Fig. 4a). No main effect of Hemisphere or interaction between Condition and Hemisphere was found for the N100m [$\beta_{LH} = -2.79$, $\chi^2(1) = 1.53$, $p = .216$, FDR-corrected; $\beta_{word:LH} = -1.83$, $\chi^2(1) = 1.71$, $p = .287$, FDR-corrected]. Additionally, there were main effects of Hemisphere for both the N250m [$\beta_{LH} = -3.17$, $\chi^2(1) = 7.36$, $p = .011$, FDR-corrected] and the N400m [$\beta_{LH} = -4.04$, $\chi^2(1) = 10.93$, $p = .003$, FDR-corrected], suggesting that the amplitude was higher in the right hemisphere compared to the left hemisphere. No main effect of Condition or interaction between Condition and Hemisphere was found for the N250m [$\beta_{word} = -0.55$, $\chi^2(1) = 0.05$, $p = .815$, FDR-corrected; $\beta_{word:LH} = -0.49$, $\chi^2(1) = 0.20$, $p = .658$, FDR-corrected] or the N400m [$\beta_{word} = 0.58$, $\chi^2(1) = 0.22$, $p = .815$, FDR-corrected; $\beta_{word:LH} = -1.20$, $\chi^2(1) = 2.21$, $p = .287$, FDR-corrected].

At the source level, for the N100m component, an amplitude reduction to spoken words compared to "*mmm*" sounds was found in the left middle frontal gyrus (MFG) and the left posterior insula [$p_{tfce} < 0.05$, FDR-corrected; 118 vertices].

Moreover, a regression analysis revealed a positive age correlation of the N100m lexicality effect in the left-hemisphere sensors [$\beta = 4.18$, $t = 2.23$, adjusted $p = .033$, FDR-corrected]. When contrasting spoken words to "*mmm*" sounds, the reduced N100m responses gradually diminished with children's age (Fig. 4b). However, this age-related trend was not observed in the right-hemisphere sensors [$\beta = 0.40$, $t = 0.25$, adjusted $p = .403$, FDR-corrected].

A whole-brain regression analysis showed a similar positive age correlation in the left precuneus [adjusted $p < .05$, FDR-corrected; 79 vertices,] and the left ventral occipitotemporal cortex (vOTC) [adjusted $p < .05$, FDR-corrected; 60 vertices] (Fig. 4c).

3.2.5. *Phrase-level contextual effect in adults: amplitude reduction in P200m and N400m*

At the sensor level, the main effects of Condition were found for the P200m [$\beta_{phrase} = -6.03$, $\chi^2(1) = 9.36$, $p = .004$, FDR-corrected] and the N400m [$\beta_{phrase} = -2.59$, $\chi^2(1) = 7.31$, $p = .007$, FDR-corrected], with reduced responses to words in phrasal contexts (e.g., "*green glass*") than words with no context (e.g., "*mmm glass*") in adults. Neither a main effect of Hemisphere nor an interaction between Condition and

Hemisphere was observed for the P200m [$\beta_{LH} = -0.92$, $\chi^2(1) = 0.67$, $p = .670$, FDR-corrected; $\beta_{phrase:LH} = -0.02$, $\chi^2(1) = 0.00$, $p = .984$, FDR-corrected] or N400m [$\beta_{LH} = -0.36$, $\chi^2(1) = 0.18$, $p = .670$, FDR-corrected; $\beta_{phrase:LH} = 0.04$, $\chi^2(1) = 0.01$, $p = .984$, FDR-corrected].

At the source level, the context-induced reduction in P200m was observed in the left hemisphere [$p_{tfce} < 0.05$, FDR-corrected; 348 vertices], including insula, pre-/post-central gyrus, anterior temporal lobe, and inferior parietal lobule, as well as the in the right hemispheres [$p_{tfce} < 0.05$, FDR-corrected; 283 vertices], including MFG, SMG, and anterior cingulate cortex. (Fig. 5).

3.2.6. Phrase-level contextual effect in children: enhanced N400m responses to two-word phrases

At the sensor level, the main effects of Hemisphere were found for the N250m [$\beta_{LH} = -3.59$, $\chi^2(1) = 7.49$, $p = .010$, FDR-corrected] and the N400m [$\beta_{LH} = -3.40$, $\chi^2(1) = 6.72$, $p = .010$, FDR-corrected], with higher amplitudes in the right hemisphere than the left hemisphere across conditions in children (Fig. 5). No main effects of Condition or interactions between Condition and Hemisphere were observed for the N250m [$\beta_{phrase} = -0.94$, $\chi^2(1) = 0.51$, $p = .612$, FDR-corrected; $\beta_{phrase:LH} = 0.66$, $\chi^2(1) = 0.51$, $p = .656$, FDR-corrected] or the N400m [$\beta_{phrase} = 0.64$, $\chi^2(1) = 0.26$, $p = .612$, FDR-corrected; $\beta_{phrase:LH} = 0.28$, $\chi^2(1) = 0.20$, $p = .656$, FDR-corrected].

At the source level, cluster-based permutation tests revealed that children showed increased N400m responses to the words in a phrasal context compared to those without context in the right temporal lobe [$p_{tfce} < 0.05$, FDR-corrected; 203 vertices]. However, regression analyses did not show any age correlation for the N250m or the N400m at either the sensor or source level.

4. Discussion

The present study used MEG to investigate auditory evoked responses and hemispheric asymmetries at different levels of linguistic processing in school-age children and adults. At the sound level, reduced brain responses to repeated sounds were observed in the N100m and P200m components in adults, as well as in the N100m component in children. At the word level, adults showed an increased signal for the lexicality effect (word vs. "*mmm*") in the left SMG during the P200m time window. In contrast, children exhibited a decreased signal for the same comparision in the left MFG and the left posterior insula during the N100m time window. Regression analyses further revealed that children's age positively correlated with the N100m lexicality effect in the left precuneus and left vOTC. Lastly, at the phrase level, adults displayed a general signal reduction to words in a phrasal context compared to those without context during the P200m time window. Conversely, children exhibited enhanced N400m activation induced by the phrasal context in the right temporal lobe.

4.1. Adults and children exhibited repetition suppression in the early auditory components

Both children and adults showed a repetition suppression for their early auditory evoked responses, indicating an adaptation mechanism to repeated sensory input for processing efficiency (Grill-Spector et al., 2006). In the adult group, a widely distributed N100m repetition suppression was observed in both hemispheres. Additionally, the P200m repetition suppression was localized in regions across the frontal, anterior temporal, and medial parts of the left hemisphere. This widely distributed pattern could be due to the point-spread functions (PSFs) we

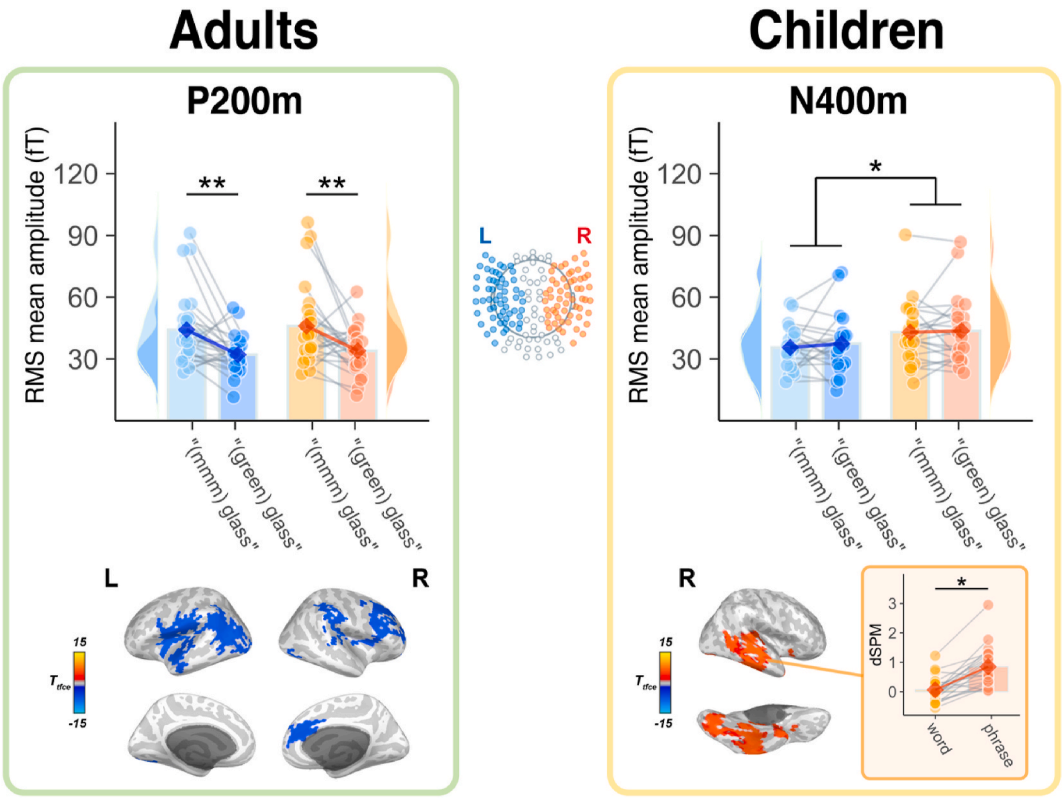


Fig. 5. Phrase-level contextual effect in adults and children. Left panel: RMS mean amplitudes of P200m and corresponding source localization in the adult group. Right panel: RMS mean amplitudes of N400m and corresponding source localization in the child group, along with a bar plot indicating the mean amplitudes in the left temporal cluster for word and phrase conditions. The sensors of interest in the left and right hemispheres and the corresponding brain signals are indicated by blue and orange, respectively. Significant levels for sensor-level results are denoted by asterisks (*$p < .05$, **$p < .01$, ***$p < .001$; FDR-corrected). Source-level results were set at the FDR-corrected threshold of p (TFCE) < 0.05. L: left; R: right.

implemented in the source analysis, which might blur the overall estimation because of signal leakage between sources. Other methods, such as cross-talk functions (CTFs), should be utilized together with PSFs in future studies to enhance the accuracy of source localization (Hauk et al., 2022).

As for children, the N100m repetition suppression was observed at the sensor level. Our findings are consistent with a previous MEG study by Orekhova et al. (2013), which showed that children (ages 7–16 years) exhibited reduced brain responses to the repetition of white noise clicks (a pair of clicks with a 1,000 ms interstimulus interval (ISI)) at the sensor level and in their auditory cortices in both hemispheres during the early time window (50–130 ms). However, we did not find any significant clusters at the source level. This could be attributed to the slow maturation of auditory cortex during childhood. Moore and Linthicum (2007) indicated that 6–12 years of age is the stage of axonal maturation in the superficial layers of auditory cortex. Consequently, children may not have adult-like axon density in their auditory systems until ages 11 or 12. This slow maturation of auditory cortical layers may affect dipole signals, complicating the measurement of children's auditory evoked responses using M/EEG methods. Thus, individual differences in brain structure within the child group could hinder the accurate estimation of their brain responses at the source level. Future studies should include participants' structural images and use a longitudinal design to better capture the developmental profiles of children's auditory processing.

Unlike adults, who demonstrated repetition suppression for both the N100m and P200m components, children did not exhibit repetition suppression in the later component, such as the N250m. Previous M/EEG studies have reported enhanced brain responses around 200–250 ms to the repetition of pure tones in school-age children (ages 9–10 years across studies) (Karhu et al. (1997): tone sequences (four consecutive 800 Hz pure tones with a 1,000 ms ISI; Ruhnau et al. (2011): repetitive tones (500 Hz pure tones) presented with a 500 ms stimulus onset asynchrony (SOA) in a block). Given the broader age range in the child group in the present study, the absence of N250m repetition suppression in children may be due to a cancelling-out effect, where some children showed signal reduction while others showed signal enhancement in response to repeated sounds. A larger sample size across different age cohorts in future studies will be necessary to characterize the developmental changes to stimulus repetition within auditory modality.

4.2. Adults showed P200m lexicality effect in the left SMG

In line with a previous MEG study investigating lexicality effects by comparing spoken words and pseudowords (MacGregor et al., 2012), an increased P200m response to adjective words compared to "*mmm*" sounds was found in the adult group. Source analysis further localized the lexicality effect to the left SMG. Previous research has indicated that the left SMG and adjacent regions in the left IPL may be involved in lexical representation (Gow and Olson, 2016) or audiovisual mapping (Bonte et al., 2017) during language comprehension. A meta-analysis of fMRI studies on the lexicality effect in the auditory modality found that, compared to pseudowords, spoken words elicited greater activation in the temporal lobe and IPL (Davis and Gaskell, 2009). However, in addition to the lexical representation, these regions have been shown to be involved in other processes, such as sensorimotor integration, as well as articulatory and phonological processing (Hickok and Poeppel, 2007; McQueen et al., 2016; Oberhuber et al., 2016). The design in our current study could not rule out the possibility that these other processes were involved during spoken word recognition. Further research would be necessary to better delineate these processes when comprehending spoken words.

4.3. Left-hemisphere N100m responses to lexicality correlated with children's age

Similar to previous research on lexicality effects in children (ages 4–8 years; Caffarra et al., 2017), we observed decreased responses to words relative to the "*mmm*" sounds in their early auditory component. Moreover, a positive correlation between age and the size of N100m lexicality effect was found at the left-hemisphere sensors as well as in the left precuneus and the left vOTC. The age correlation of N100m lexicality in children may be associated with the efficiency of phonological processing and automatic orthographic mapping during spoken word recognition with increasing age. Pugh et al. (2013) investigated the relationship between children's (ages 5–9 years) reading-relevant skills, such as phonological awareness and decoding, and their brain responses to print and spoken (pseudo)words using fMRI. They found that, for speech-related processing, children's reading-relevant skills were positively correlated with brain activation in the left IFG and precuneus. In another longitudinal fMRI studies investigating phonological processing in children at different reading stages (pre-reading, beginning reading, emergent reading), Yu et al. (2018) observed decreased activation in the left IPL and bilateral precuneus during an audiovisual phonological task across three time points. They suggested that this developmental decrease in the left IPL and precuneus indicates the increasing efficiency in phonological processing with children's age. Additionally, the age correlation that we observed in the left vOTC is in line with the findings of Monzalvo and Dehaene-Lambertz (2013). They found that older children (9 years old) with more reading experience showed greater activation in the VWFA, suggesting that, with increasing age, greater language experience may result in automatic activation of reading-related brain areas for orthographic codes during spoken word recognition in children.

4.4. Adults showed reduced P200m responses in phrasal contexts

Adults showed a general signal reduction to the phrase condition (e.g., "*green glass*") compared to the one-word condition (e.g., "*mmm glass*") in both sensor and source space. This may be due to predictive processing when listening to adjective-noun phrases. This contrasts with previous literature on the effects of basic composition in adjective-noun phrases, which has generally shown a signal increase in temporal and prefrontal cortices for phrasal as compared to non-combinatory stimuli (Bemis and Pylkkänen, 2011, 2013). However, only one of those studies has used the auditory modality in comprehension (Bemis and Pylkkänen, 2013). The present study differs from the prior studies in that it included a baseline condition, in which both stimulus slots were filled with the "*mmm*" sound. This resulted in a difference between the probability of a noun after an adjective (100 %) and the probability of a noun after "*mmm*" (50 %). This is a possible explanation for the reduced signals in the phrase condition: in this condition, when participants heard the adjective, they were able to expect that the second word would be an object noun. By contrast, when participants heard an "*mmm*" sound in the first-word position, they had less chance to predict the next stimulus since there were two potential candidates (object nouns or "*mmm*" sounds) in the second-word position. Therefore, the different probabilities between the conditions may have resulted in a reduction in the phrase condition, reflecting expectancy or the ease of information integration when listening to words in the phrasal context.

4.5. Children showed enhanced right-hemisphere N400m responses in phrasal contexts

Children exhibited increased N400m responses in the right temporal regions to words in phrasal contexts as compared to those without context. This finding aligns with a previous EEG study indicating that school-age children showed right-hemisphere dominance in their brain responses when listening to spoken sentences (Abrams et al., 2008). However, our finding on children's N400m component differs from the contextual effect reported in Hahne et al. (2004). In their EEG study, children over the age of 7 exhibited early anterior negativities, an indicator of automatic processing of syntactic structure, in response to

syntactic anomalies in sentences. This discrepancy may be due to differences in stimuli (longer phrases in Hahne et al. (2004)), tasks (grammaticality judgment vs. picture matching), and research focus (error detection vs. composition) between the two studies.

Our findings that adults exhibited P200m signal reduction while children showed N400m signal enhancement may be due to different strategies employed by adults and children during phrase- or sentence-level comprehension. For example, research on age-related differences in comprehending referential expression has indicated that adults focus more on the grammatical information, whereas children prioritize descriptive information in referential contexts (Brody and Feiman, 2024). Additionally, studies using neuroimaging techniques have shown that children rely more on semantic-based processing during language comprehension (Dube et al., 2019; Morgan et al., 2020; J. M. Schneider et al., 2016; Skeide et al., 2014). For instance, Schneider et al. (2016) found that in an auditory grammaticality judgment task, adults elicited P600 responses, whereas children (ages 10–12) elicited N400 responses to ungrammatical sentences compared to grammatical sentences. This impact of experience or proficiency on language processing can also be observed in second language learners. For instance, Weber-Fox and Neville (1996) investigated the effect of language exposure in Chinese/English bilinguals and found that, unlike native speakers who showed a P600 effect, bilinguals with later exposures to English (i.e., after the age of 16) exhibited N400-like negativity with bilateral distribution to syntactic anomalies. The convergence of children's and late bilinguals' N400-like response to anomalies during sentence comprehension suggests that language experience (operationalized by either age or language exposure) can modulate the effect we observed in phrase- or sentence-level processing. Furthermore, a similar pattern of greater involvement of the right hemisphere was found in English adult native speakers after they learned Mandarin Chinese through a 4-week course (Qi et al., 2015). Our results, which show increased right-hemisphere N400m in children, support the view that an individual's language experience or proficiency can influence the involvement of right hemisphere when processing phrase- or sentence-level information.

4.6. Limitations

The task reported here incorporated design components aligned with the objectives of the larger protocol it was part of, which led to certain limitations. Firstly, the inclusion of the baseline condition introduced a probability contrast between the one-word and phrase conditions, resulting in a co-variation of composition and predictability. Additionally, in selecting a non-lexical stimulus, we prioritized naturalness, opting for an ecologically valid hesitation sound ("*mmm*") rather than a nonword matched in phonetic detail to the corresponding lexical stimulus. This leaves room to explore the contribution of phonological processes to the observed lexicality effects. While the role of predictability will be more straightforward for future studies to address, disentangling lexical processing from phonological processing is always a challenge. This is because stimuli that possess the phonological properties of real words generally trigger lexical activation, even if they themselves lack meaning.

In the present study, we did not collect participant's MRI structural images; instead, we used adult and child templates for data preprocessing. Therefore, our results of source analysis should be interpreted with caution. Moreover, our results demonstrated developmental trajectories at different levels of processing, but the sample size in our child group was relatively small. Future studies should include a larger sample size of children at different age cohorts.

Previous research has shown that children's language abilities can mediate their brain responses (Joo et al., 2021; Monzalvo and Dehaene-Lambertz, 2013; Pugh et al., 2013; Sanchez-Alonso and Aslin, 2020). Furthermore, recent studies have indicated socioeconomic status (SES) and neighborhood poverty as important factors associated with children's brain development (Amso, 2020; J. Schneider et al., 2021; J. M. Schneider et al., 2024; Thanaraju et al., 2024). Therefore, comprehensive assessments of language-related skills and cognitive functions, as well as large-scale studies across diverse regions and countries, are needed in the future research for a better understanding of individual differences and environmental contributions to linguistic processing and the underlying developmental changes in children's brains.

5. Conclusions

In sum, our study revealed a variety of developmental trajectories and hemispheric asymmetries at different levels of linguistic processing in children. At the basic sound level, children exhibited adult-like adaptation to repeated sounds. At the word level, the size of the lexicality effect in the N100m was associated with children's age. This age correlation was observed in the left precuneus and vOTC, suggesting age-related changes in phonological processing efficiency and automatic access to orthographic information during spoken word recognition. Additionally, when comprehending words in a phrasal context, children showed increased responses during the N400m time window in the right temporal lobe, indicating greater recruitment of right-hemisphere resources for phrase comprehension.

CRediT authorship contribution statement

Marco C.H. Lai: Writing – original draft, Investigation, Conceptualization, Writing – review & editing, Visualization, Formal analysis. **Ellie Abrams:** Project administration, Investigation, Methodology. **Sherine Bou Dargham:** Project administration, Investigation. **Jacqui Fallon:** Project administration, Investigation. **Ebony Goldman:** Project administration, Investigation. **Miriam Hauptman:** Project administration, Investigation. **Alicia Parrish:** Project administration, Investigation. **Sarah F. Phillips:** Project administration, Investigation. **Alejandra Reinoso:** Project administration, Investigation. **Liina Pylkkänen:** Writing – review & editing, Methodology, Funding acquisition, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgments

This work was supported by the NSF Award BCS-1923144 (LP) and award G1001 from NYUAD Institute, New York University Abu Dhabi (LP). We thank Ria Geguera for contributing to recruitment and data collection and Jeff Walker for assistance with data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2025.109219.

Data availability

Data will be made available on request.

References

Abrams, D.A., Nicol, T., Zecker, S., Kraus, N., 2008. Right-hemisphere auditory cortex is dominant for coding syllable patterns in speech. Journal of Neuroscience 28 (15), 3958–3965. https://doi.org/10.1523/JNEUROSCI.0187-08.2008.

Albrecht, R., von Suchodoletz, W., Uwer, R., 2000. The development of auditory evoked dipole source activity from childhood to adulthood. Clin. Neurophysiol. 111 (12), 2268–2276. https://doi.org/10.1016/S1388-2457(00)00464-8.

Amso, D., 2020. Neighborhood poverty and brain development: adaptation or maturation, fixed or reversible? JAMA Netw. Open 3 (11), e2024139. https://doi.org/10.1001/jamanetworkopen.2020.24139.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Software 67 (1). https://doi.org/10.18637/jss.v067.i01.
Bemis, D.K., Pylkkänen, L., 2011. Simple composition: a magnetoencephalography investigation into the comprehension of minimal linguistic phrases. J. Neurosci. 31 (8), 2801–2814. https://doi.org/10.1523/JNEUROSCI.5003-10.2011.
Bemis, D.K., Pylkkänen, L., 2013. Basic linguistic composition recruits the left anterior temporal lobe and left angular gyrus during both listening and reading. Cerebr. Cortex 23 (8), 1859–1873. https://doi.org/10.1093/cercor/bhs170.
Benjamini, Y., Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J. Roy. Stat. Soc. B 57 (1), 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x.
Berl, M.M., Mayo, J., Parks, E.N., Rosenberger, L.R., VanMeter, J., Ratner, N.B., Vaidya, C.J., Gaillard, W.D., 2014. Regional differences in the developmental trajectory of lateralization of the language network: Developmental trajectories of lateralization of language. Hum. Brain Mapp. 35 (1), 270–284. https://doi.org/10.1002/hbm.22179.
Bishop, D.V.M., Hardiman, M.J., Barry, J.G., 2011. Is auditory discrimination mature by middle childhood? A study using time-frequency analysis of mismatch responses from 7 years to adulthood: is auditory discrimination mature? Dev. Sci. 14 (2), 402–416. https://doi.org/10.1111/j.1467-7687.2010.00990.x.
Bishop, D.V.M., Hardiman, M., Uwer, R., von Suchodoletz, W., 2007. Maturation of the long-latency auditory ERP: step function changes at start and end of adolescence. Dev. Sci. 10 (5), 565–575. https://doi.org/10.1111/j.1467-7687.2007.00619.x.
Bonte, M., Correia, J.M., Keetels, M., Vroomen, J., Formisano, E., 2017. Reading-induced shifts of perceptual speech representations in auditory cortex. Sci. Rep. 7 (1), 5143. https://doi.org/10.1038/s41598-017-05356-3.
Brem, S., Bach, S., Kucian, K., Kujala, J.V., Guttorm, T.K., Martin, E., Lyytinen, H., Brandeis, D., Richardson, U., 2010. Brain sensitivity to print emerges when children learn letter–speech sound correspondences. Proc. Natl. Acad. Sci. 107 (17), 7939–7944. https://doi.org/10.1073/pnas.0904402107.
Brody, G., Feiman, R., 2024. Mapping words to the world: Adults, but not children, understand how mismatching descriptions refer. Journal of Experimental Psychology: General 153 (4), 1053–1065. https://doi.org/10.1037/xge000154.
Bruzzone, S.E.P., Haumann, N.T., Kliuchko, M., Vuust, P., Brattico, E., 2021. Applying Spike-density component analysis for high-accuracy auditory event-related potentials in children. Clin. Neurophysiol. 132 (8), 1887–1896. https://doi.org/10.1016/j.clinph.2021.05.007.
Caffarra, S., Martin, C.D., Lizarazu, M., Lallier, M., Zarraga, A., Molinaro, N., Carreiras, M., 2017. Word and object recognition during reading acquisition: MEG evidence. Dev. Cognit. Neurosci. 24, 21–32. https://doi.org/10.1016/j.dcn.2017.01.002.
Cheng, X., Schafer, G., Riddell, P.M., 2014. Immediate auditory repetition of words and nonwords: an ERP study of lexical and sublexical processing. PLoS One 9 (3), e91988. https://doi.org/10.1371/journal.pone.0091988.
Dale, A.M., Liu, A.K., Fischl, B.R., Buckner, R.L., Belliveau, J.W., Lewine, J.D., Halgren, E., 2000. Dynamic statistical parametric mapping. Neuron 26 (1), 55–67. https://doi.org/10.1016/S0896-6273(00)81138-1.
Davis, M.H., Gaskell, M.G., 2009. A complementary systems account of word learning: neural and behavioural evidence. Phil. Trans. Biol. Sci. 364 (1536), 3773–3800. https://doi.org/10.1098/rstb.2009.0111.
Desikan, R.S., Ségonne, F., Fischl, B., Quinn, B.T., Dickerson, B.C., Blacker, D., Buckner, R.L., Dale, A.M., Maguire, R.P., Hyman, B.T., Albert, M.S., Killiany, R.J., 2006. An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. Neuroimage 31 (3), 968–980. https://doi.org/10.1016/j.neuroimage.2006.01.021.
Dube, S., Kung, C., Brock, J., Demuth, K., 2019. Perceptual salience and the processing of subject-verb agreement in 9–11-year-old English-speaking children: evidence from ERPs. Lang. Acquis. 26 (1), 73–96. https://doi.org/10.1080/10489223.2017.1394305.
Engemann, D.A., Gramfort, A., 2015. Automated model selection in covariance estimation and spatial whitening of MEG and EEG signals. Neuroimage 108, 328–342. https://doi.org/10.1016/j.neuroimage.2014.12.040.
Fonov, V., Evans, A.C., Botteron, K., Almli, C.R., McKinstry, R.C., Collins, D.L., 2011. Unbiased average age-appropriate atlases for pediatric studies. Neuroimage 54 (1), 313–327. https://doi.org/10.1016/j.neuroimage.2010.07.033.
Gow, D.W., Olson, B.B., 2016. Sentential influences on acoustic-phonetic processing: a granger causality analysis of multimodal imaging data. Lang. Cognit. Neurisci. 31 (7), 841–855. https://doi.org/10.1080/23273798.2015.1029498.
Gramfort, A., 2013. MEG and EEG data analysis with MNE-python. Front. Neurosci. 7. https://doi.org/10.3389/fnins.2013.00267.
Grill-Spector, K., Henson, R., Martin, A., 2006. Repetition and the brain: neural models of stimulus-specific effects. Trends Cognit. Sci. 10 (1), 14–23. https://doi.org/10.1016/j.tics.2005.11.006.
Hahne, A., Eckstein, K., Friederici, A.D., 2004. Brain signatures of syntactic and semantic processes during children's language development. J. Cognit. Neurosci. 16 (7), 1302–1318. https://doi.org/10.1162/0898929041920504.
Hasting, A.S., Kotz, S.A., 2008. Speeding up syntax: on the relative timing and automaticity of local phrase structure and morphosyntactic processing as reflected in event-related brain potentials. J. Cognit. Neurosci. 20 (7), 1207–1219. https://doi.org/10.1162/jocn.2008.20083.
Hauk, O., Stenroos, M., Treder, M.S., 2022. Towards an objective evaluation of EEG/MEG source estimation methods – the linear approach. Neuroimage 255, 119177. https://doi.org/10.1016/j.neuroimage.2022.119177.
Haumann, N.T., Hansen, B., Huotilainen, M., Vuust, P., Brattico, E., 2020. Applying stochastic spike train theory for high-accuracy human MEG/EEG. J. Neurosci. Methods 340, 108743. https://doi.org/10.1016/j.jneumeth.2020.108743.
Hickok, G., Poeppel, D., 2007. The cortical organization of speech processing. Nat. Rev. Neurosci. 8 (5), 393–402. https://doi.org/10.1038/nrn2113.
Holcomb, P.J., Coffey, S.A., Neville, H.J., 1992. Visual and auditory sentence processing: a developmental analysis using event-related brain potentials. Dev. Neuropsychol. 8 (2–3), 203–241. https://doi.org/10.1080/87565649209540525.
Holland, S.K., Vannest, J., Mecoli, M., Jacola, L.M., Tillema, J.-M., Karunanayaka, P.R., Schmithorst, V.J., Yuan, W., Plante, E., Byars, A.W., 2007. Functional MRI of language lateralization during development in children. Int. J. Audiol. 46 (9), 533–551. https://doi.org/10.1080/14992020701448994.
Howard, M.F., Poeppel, D., 2009. Hemispheric asymmetry in mid and long latency neuromagnetic responses to single clicks. Hear. Res. 257 (1–2), 41–52. https://doi.org/10.1016/j.heares.2009.07.010.
Joo, S.J., Tavabi, K., Caffarra, S., Yeatman, J.D., 2021. Automaticity in the reading circuitry. Brain Lang. 214, 104906. https://doi.org/10.1016/j.bandl.2020.104906.
Kadis, D.S., Pang, E.W., Mills, T., Taylor, M.J., McAndrews, M.P., Smith, M.L., 2011. Characterizing the normal developmental trajectory of expressive language lateralization using magnetoencephalography. J. Int. Neuropsychol. Soc. 17 (5), 896–904. https://doi.org/10.1017/S1355617711000932.
Karhu, J., Herrgård, E., Pääkkönen, A., Luoma, L., Airaksinen, E., Partanen, J., 1997. Dual cerebral processing of elementary auditory input in children. Neuroreport 8 (6), 1327–1330. https://doi.org/10.1097/00001756-199704140-00002.
Kolozsvári, O.B., Xu, W., Gerike, G., Parviainen, T., Nieminen, L., Noiray, A., Hämäläinen, J.A., 2021. Coherence between brain activation and speech envelope at word and sentence levels showed age-related differences in low frequency bands. Neurobiol. Lang. 2 (2), 226–253. https://doi.org/10.1162/nol_a_00033.
Kuhl, P.K., 2004. Early language acquisition: cracking the speech code. Nat. Rev. Neurosci. 5 (11), 831–843. https://doi.org/10.1038/nrn1533.
Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2017. lmerTest package: tests in linear mixed effects models. J. Stat. Software 82 (13). https://doi.org/10.18637/jss.v082.i13.
Larson, E., Maddox, R.K., Lee, A.K.C., 2014. Improving spatial localization in MEG inverse imaging by leveraging intersubject anatomical differences. Front. Neurosci. 8. https://doi.org/10.3389/fnins.2014.00330.
Litovsky, R., 2015. Development of the auditory system. In: Handbook of Clinical Neurology, vol.129. Elsevier, pp. 55–72. https://doi.org/10.1016/B978-0-444-62630-1.00003-2.
MacGregor, L.J., Pulvermüller, F., van Casteren, M., Shtyrov, Y., 2012. Ultra-rapid access to words in the brain. Nat. Commun. 3 (1), 711. https://doi.org/10.1038/ncomms1715.
Mahajan, Y., McArthur, G., 2012. Maturation of auditory event-related potentials across adolescence. Hear. Res. 294 (1–2), 82–94. https://doi.org/10.1016/j.heares.2012.10.005.
Maris, E., Oostenveld, R., 2007. Nonparametric statistical testing of EEG- and MEG-data. J. Neurosci. Methods 164 (1), 177–190. https://doi.org/10.1016/j.jneumeth.2007.03.024.
McMurray, B., Apfelbaum, K.S., Tomblin, J.B., 2022. The slow development of real-time processing: spoken-word recognition as a crucible for new thinking about language acquisition and language disorders. Curr. Dir. Psychol. Sci. 31 (4), 305–315. https://doi.org/10.1177/09637214221078325.
McQueen, J.M., Eisner, F., Norris, D., 2016. When brain regions talk to each other during speech processing, what are they talking about? Commentary on Gow and Olson (2015). Lang. Cognit. Neurisci. 31 (7), 860–863. https://doi.org/10.1080/23273798.2016.1154975.
Monzalvo, K., Dehaene-Lambertz, G., 2013. How reading acquisition changes children's spoken language network. Brain Lang. 127 (3), 356–365. https://doi.org/10.1016/j.bandl.2013.10.009.
Moore, J.K., Linthicum, F.H., 2007. The human auditory system: a timeline of development. Int. J. Audiol. 46 (9), 460–478. https://doi.org/10.1080/14992020701383019.
Morgan, E.U., van der Meer, A., Vulchanova, M., Blasi, D.E., Baggio, G., 2020. Meaning before grammar: a review of ERP experiments on the neurodevelopmental origins of semantic processing. Psychonomic Bull. Rev. 27 (3), 441–464. https://doi.org/10.3758/s13423-019-01677-8.
Muenssinger, J., Stingl, K.T., Matuz, T., Binder, G., Ehehalt, S., Preissl, H., 2013. Auditory habituation to simple tones: reduced evidence for habituation in children compared to adults. Front. Hum. Neurosci. 7. https://doi.org/10.3389/fnhum.2013.00377.
Näätänen, R., Picton, T., 1987. The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. Psychophysiology 24 (4), 375–425. https://doi.org/10.1111/j.1469-8986.1987.tb00311.x.
Oberhuber, M., Hope, T.M.H., Seghier, M.L., Parker Jones, O., Prejawa, S., Green, D.W., Price, C.J., 2016. Four functionally distinct regions in the left supramarginal gyrus support word processing. Cerebr. Cortex 26 (11), 4212–4226. https://doi.org/10.1093/cercor/bhw251.
Olulade, O.A., Seydell-Greenwald, A., Chambers, C.E., Turkeltaub, P.E., Dromerick, A.W., Berl, M.M., Gaillard, W.D., Newport, E.L., 2020. The neural basis of language development: changes in lateralization over age. Proc. Natl. Acad. Sci. 117 (38), 23477–23483. https://doi.org/10.1073/pnas.1905590117.
Oostenveld, R., Fries, P., Maris, E., Schoffelen, J.-M., 2011. FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. Comput. Intell. Neurosci. 2011, 1–9. https://doi.org/10.1155/2011/156869.
Orekhova, E.V., Butorina, A.V., Tsetlin, M.M., Novikova, S.I., Sokolov, P.A., Elam, M., Stroganova, T.A., 2013. Auditory magnetic response to clicks in children and adults: its components, hemispheric lateralization and repetition suppression effect. Brain Topogr. 26 (3), 410–427. https://doi.org/10.1007/s10548-012-0262-x.

Paetau, R., Ahonen, A., Salonen, O., Sams, M., 1995. Auditory evoked magnetic fields to tones and pseudowords in healthy children and adults. J. Clin. Neurophysiol. 12 (2), 177–185. https://doi.org/10.1097/00004691-199503000-00008.

Pang, E.W., Taylor, M.J., 2000. Tracking the development of the N1 from age 3 to adulthood: an examination of speech and non-speech stimuli. Clin. Neurophysiol. 111 (3), 388–397. https://doi.org/10.1016/S1388-2457(99)00259-X.

Parviainen, T., Helenius, P., Salmelin, R., 2019. Children show hemispheric differences in the basic auditory response properties. Hum. Brain Mapp. 40 (9), 2699–2710. https://doi.org/10.1002/hbm.24553.

Pernet, C.R., Chauveau, N., Gaspar, C., Rousselet, G.A., 2011. Limo EEG: a toolbox for hierarchical linear modeling of electroencephalographic data. Comput. Intell. Neurosci. 2011, 1–11. https://doi.org/10.1155/2011/831409.

Ponton, C.W., Eggermont, J.J., Khosla, D., Kwong, B., Don, M., 2002. Maturation of human central auditory system activity: separating auditory evoked potentials by dipole source modeling. Clin. Neurophysiol. 113 (3), 407–420. https://doi.org/10.1016/S1388-2457(01)00733-7.

Ponton, C.W., Eggermont, J.J., Kwong, B., Don, M., 2000. Maturation of human central auditory system activity: evidence from multi-channel evoked potentials. Clin. Neurophysiol. 111 (2), 220–236. https://doi.org/10.1016/S1388-2457(99)00236-9.

Pugh, K.R., Landi, N., Preston, J.L., Mencl, W.E., Austin, A.C., Sibley, D., Fulbright, R.K., Seidenberg, M.S., Grigorenko, E.L., Constable, R.T., Molfese, P., Frost, S.J., 2013. The relationship between phonological and auditory processing and brain organization in beginning readers. Brain Lang. 125 (2), 173–183. https://doi.org/10.1016/j.bandl.2012.04.004.

Qi, Z., Han, M., Garel, K., San Chen, E., Gabrieli, J.D.E., 2015. White-matter structure in the right hemisphere predicts Mandarin Chinese learning success. J. Neurolinguistics 33, 14–28. https://doi.org/10.1016/j.jneuroling.2014.08.004.

R Core Team, 2020. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria [Computer software]. https://www.R-project.org/.

Ruhnau, P., Herrmann, B., Maess, B., Schröger, E., 2011. Maturation of obligatory auditory responses and their neural sources: evidence from EEG and MEG. Neuroimage 58 (2), 630–639. https://doi.org/10.1016/j.neuroimage.2011.06.050.

Sanchez-Alonso, S., Aslin, R.N., 2020. Predictive modeling of neurobehavioral state and trait variation across development. Dev. Cognit. Neurosci. 45, 100855. https://doi.org/10.1016/j.dcn.2020.100855.

Satterthwaite, F.E., 1941. Synthesis of variance. Psychometrika 6 (5), 309–316. https://doi.org/10.1007/BF02288586.

Schneider, J., Abel, A.D., Momsen, J., Melamed, T.C., Maguire, M.J., 2021. Neural oscillations reveal differences in the process of word learning among school-aged children from lower socioeconomic status backgrounds. Neurobiol. Lang. 1–17. https://doi.org/10.1162/nol_a_00040.

Schneider, J.M., Abel, A.D., Ogiela, D.A., Middleton, A.E., Maguire, M.J., 2016. Developmental differences in beta and theta power during sentence processing. Dev. Cognit. Neurosci. 19, 19–30. https://doi.org/10.1016/j.dcn.2016.01.001.

Schneider, J.M., Kim, J., Poudel, S., Lee, Y.S., Maguire, M.J., 2024. Socioeconomic status (SES) and cognitive outcomes are predicted by resting-state EEG in school-aged children. Dev. Cognit. Neurosci. 70, 101468. https://doi.org/10.1016/j.dcn.2024.101468.

Segaert, K., Mazaheri, A., Hagoort, P., 2018. Binding language: structuring sentences through precisely timed oscillatory mechanisms. Eur. J. Neurosci. 48 (7), 2651–2662. https://doi.org/10.1111/ejn.13816.

Shibasaki, H., Miyazaki, M., 1992. Event-related potential studies in infants and children. J. Clin. Neurophysiol. 9 (3), 408–418. https://doi.org/10.1097/00004691-199207010-00007.

Skeide, M.A., Brauer, J., Friederici, A.D., 2014. Syntax gradually segregates from semantics in the developing brain. Neuroimage 100, 106–111. https://doi.org/10.1016/j.neuroimage.2014.05.080.

Smith, S., Nichols, T., 2009. Threshold-free cluster enhancement: addressing problems of smoothing, threshold dependence and localisation in cluster inference. Neuroimage 44 (1), 83–98. https://doi.org/10.1016/j.neuroimage.2008.03.061.

Sussman, E., Steinschneider, M., Gumenyuk, V., Grushko, J., Lawson, K., 2008. The maturation of human evoked brain potentials to sounds presented at different stimulus rates. Hear. Res. 236 (1–2), 61–79. https://doi.org/10.1016/j.heares.2007.12.001.

Szaflarski, J.P., Holland, S.K., Schmithorst, V.J., Byars, A.W., 2006a. fMRI study of language lateralization in children and adults. Hum. Brain Mapp. 27 (3), 202–212. https://doi.org/10.1002/hbm.20177.

Szaflarski, J.P., Schmithorst, V.J., Altaye, M., Byars, A.W., Ret, J., Plante, E., Holland, S. K., 2006b. A longitudinal functional magnetic resonance imaging study of language development in children 5 to 11 years old. Ann. Neurol. 59 (5), 796–807. https://doi.org/10.1002/ana.20817.

Takeshita, K., Nagamine, T., Thuy, D.H.D., Satow, T., Matsuhashi, M., Yamamoto, J., Takayama, M., Fujiwara, N., Shibasaki, H., 2002. Maturational change of parallel auditory processing in school-aged children revealed by simultaneous recording of magnetic and electric cortical responses. Clin. Neurophysiol. 113 (9), 1470–1484. https://doi.org/10.1016/S1388-2457(02)00202-X.

Thanaraju, A., Marzuki, A.A., Chan, J.K., Wong, K.Y., Phon-Amnuaisuk, P., Vafa, S., Chew, J., Chia, Y.C., Jenkins, M., 2024. Structural and functional brain correlates of socioeconomic status across the life span: a systematic review. Neurosci. Biobehav. Rev. 162, 105716. https://doi.org/10.1016/j.neubiorev.2024.105716.

Tremblay, K.L., Shahin, A.J., Picton, T., Ross, B., 2009. Auditory training alters the physiological detection of stimulus-specific cues in humans. Clin. Neurophysiol. 120 (1), 128–135. https://doi.org/10.1016/j.clinph.2008.10.005.

van Bijnen, S., Kärkkäinen, S., Helenius, P., Parviainen, T., 2019. Left hemisphere enhancement of auditory activation in language impaired children. Sci. Rep. 9 (1), 9087. https://doi.org/10.1038/s41598-019-45597-y.

Weber-Fox, C.M., Neville, H.J., 1996. Maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. J. Cognit. Neurosci. 8 (3), 231–256. https://doi.org/10.1162/jocn.1996.8.3.231.

Weiss-Croft, L.J., Baldeweg, T., 2015. Maturation of language networks in children: a systematic review of 22years of functional MRI. Neuroimage 123, 269–281. https://doi.org/10.1016/j.neuroimage.2015.07.046.

Wunderlich, J.L., Cone-Wesson, B.K., 2006. Maturation of CAEP in infants and children: a review. Hear. Res. 212 (1–2), 212–223. https://doi.org/10.1016/j.heares.2005.11.008.

Yoncheva, Y.N., Zevin, J.D., Maurer, U., McCandliss, B.D., 2010. Auditory selective attention to speech modulates activity in the visual word form area. Cerebr. Cortex 20 (3), 622–632. https://doi.org/10.1093/cercor/bhp129.

Yu, X., Raney, T., Perdue, M.V., Zuk, J., Ozernov-Palchik, O., Becker, B.L.C., Raschle, N. M., Gaab, N., 2018. Emergence of the neural network underlying phonological processing from the prereading to the emergent reading stage: a longitudinal study. Hum. Brain Mapp. 39 (5), 2047–2063. https://doi.org/10.1002/hbm.23985.