

# Development of auditory change-detection and attentional capture, and their relation to inhibitory control

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## Abstract

EEG methods offer a promising approach to study the development of attention or attention-related processes such as change-detection and attentional capture. However, the development of these attention processes from early to middle childhood is not well understood. In the current study, we utilized a passive three-stimulus oddball paradigm to examine age-related changes in auditory change-detection and attentional capture in a large sample of children across childhood ( $N = 475$ ; 249 female, 226 male;  $M_{\text{age}} = 6.71$ ;  $SD_{\text{age}} = 2.22$ ;  $\text{Range}_{\text{age}} = 4.01\text{--}11.5$  years). Conventional ERP analyses revealed no age-related changes in change detection (mismatch negativity) and attentional capture (P3a) components, but we observed age-related reductions in late automatic processing of auditory change (late discriminative negativity). However, when utilizing time-frequency analyses, we observed developmental increases in frontocentral signal strength (power) and consistency (inter-trial phase synchrony) in delta and theta bands in response to novel sounds. Such frontocentral delta/theta responses have been linked in prior work to cognitive control. To further examine this possibility, we examined relations with inhibitory control. Results revealed that increased consistency in theta in response to novel sounds was related to improved inhibitory control. Together, our results advance our understanding of the development of attention in childhood. Moreover, they demonstrate the contributions of time-frequency approaches to studying neurocognitive development. Finally, our results highlight the utility of neuroimaging paradigms that have low cognitive and motor demands to study the development of psychological processes.

## KEYWORDS

children, developmental research, MMN, P3, time-frequency

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## 1 | INTRODUCTION

One of the challenges to studying the development of attention is the availability of paradigms that can measure attention across development. Most of the paradigms commonly used to study attention have important cognitive and motor demands that make it difficult for young children to successfully complete these tasks. Passive listening tasks, combined with neuroimaging methods, eliminate motor demands and reduce cognitive requirements (e.g., understanding instructions), offering promising approaches to assess attention across development. One of the most used approaches is to employ an auditory oddball paradigm while collecting EEG. Auditory oddball paradigms involve presentation of frequent/infrequent stimuli and can be used to study specific aspects of attention, such as individuals' ability to detect and discriminate among stimuli (i.e., change-detection) (Näätänen et al., 2007), and to measure attention orienting or attentional capture (Escera et al., 1998; Polich, 2007). Furthermore, differences in auditory attention-related processes have been linked to language development (Choudhury & Benasich, 2011), temperament/personality (Gurrera et al., 2001, 2005; Marshall et al., 2009; Reeb-Sutherland et al., 2009), internalizing problems (He et al., 2010; Ogura et al., 1993; Reeb-Sutherland et al., 2009), and externalizing and attention problems (Gumenyuk et al., 2005; Rothenberger et al., 2000).

Attention is often conceptualized in terms of a dichotomy between bottom-up (e.g., involuntary, exogenous) and top-down (e.g., goal-directed, endogenous) attentional systems, which are thought to rely on partially segregated brain networks (Corbetta & Shulman, 2002). However, these two systems dynamically interact (e.g., when redirecting attention in the face of novel and salient stimuli; Corbetta et al., 2008), and such interactions may be facilitated through a (partial) overlap in their neural instantiation (i.e., shared neural resources across the top-down and bottom-up attentional systems). Although it is clear auditory oddball paradigms capture bottom-up attention, EEG and fMRI studies further suggest an important overlap in the neural systems involved in bottom-up and top-down auditory attention. Evidence for this overlap across neural systems includes the engagement of frontoparietal brain networks and oscillatory dynamics that have been linked to top-down attention (Alho et al., 2015; Barceló et al., 2002, 2006; Bishop, Hardiman, & et al., 2011; Cavanagh & Frank, 2014; Huang & Elhilali, 2020; Salmi et al., 2009). The overlap in brain systems implies the presence of a common mechanism involved in top-down and bottom-up attention that may support interactions between attention systems, such as bottom-up triggering top-down attention. This raises the interesting possibility

that these passive listening tasks may capture this general mechanism and be associated with more complex forms of attention and top-down control. However, most of this work has been done with adults and the development of these attention processes is not well understood, especially during childhood—a developmental period in which attention processes change considerably. Finally, existing EEG work has primarily focused on event-related potentials (ERPs), not fully leveraging all the information within the EEG data (e.g., ignoring non-phase-locked signals). Consequently, in the current study, we utilize time-frequency analyses to better characterize the amplitude and phase of the neural responses to auditory mismatch and novel sounds, with a focus on theta and delta brain oscillations. Moreover, in order to examine if these electrophysiological measures of attention are also associated with top-down control, we evaluated their relation to behavioral measures of inhibitory control.

### 1.1 | ERPs: Mismatch negativity, late discriminative negativity, and P300

The most widely studied ERP component for investigating auditory change-detection is the mismatch negativity (MMN), which involves comparing brain activity elicited by a repeated standard sound with those elicited by a rarer deviant sound differing on some acoustic dimension (Näätänen et al., 2007). The MMN constitutes an enhanced negativity to deviant sounds, compared to standard sounds, occurring around 100–250 ms after the stimulus onset in frontocentral sites. The MMN is thought to reflect automatic detection of the change in sound between frequent (standard) and infrequent (deviant) sounds and emerges from temporal and medial frontal source generators (Deouell, 2007). Following the MMN, a second component called the late discriminative negativity (LDN) is also observed. This negative deflection occurs around 250–550 ms after post-stimulus onset with a frontocentral topography (Bishop, Hardiman, et al., 2011; Cheour et al., 2001). The LDN has been suggested to reflect further cognitive, but unconscious, processing of the change in stimulus (Čeponienė et al., 2004). However, the exact function and neural sources of the LDN remain unclear.

In addition to the standard/deviant stimuli used in oddball paradigms to elicit the MMN, some auditory oddball paradigms employ a third category of complex novel stimuli which tend to elicit the novelty P300, also referred to as the P3a component (P3a hereafter). This is a positive deflection with frontocentral distribution that peaks around 200–400 ms post-stimulus onset (Escera et al., 1998; Marshall et al., 2009). The P3a is considered to reflect the orienting response or the involuntary shifts in

attention toward novelty (Escera et al., 1998; Polich, 2007) and is thought to be generated by a widespread neuronal network involving the frontoparietal attention network (Friedman et al., 2001).

The developmental trajectories of these attention-related ERPs (MMN, LDN, P3a) are unknown, especially across early childhood. All three ERP components are present in infants and early childhood (Alho et al., 1990; Kushnerenko et al., 2002; Marshall et al., 2009; Martynova et al., 2003; Morr et al., 2002; Otte et al., 2013; Van den Heuvel et al., 2015). Although the evidence is mixed, the MMN tends to increase in magnitude from childhood to adulthood (Albrecht et al., 2000; Bishop, Anderson, et al., 2011; Kushnerenko et al., 2002; Ponton et al., 2002) and this increase is especially evident when comparing children and adults (Bishop, Hardiman, et al., 2011). In contrast to the MMN, the LDN tends to be larger in infants and children than adults (Bishop, Hardiman, et al., 2011; Cheour et al., 2001). Finally, there are limited data on the development of the P3a and the available evidence is mixed, precluding a comprehensive characterization of the development of the P3a (Riggins & Scott, 2020). Importantly, most studies examining developmental changes in ERPs have been done with relatively small samples (~50–100 participants). Therefore, data from large samples of children are needed to help elucidate some of the mixed developmental findings.

## 1.2 | Time-frequency analyses

One potential explanation for the lack of consistency in the available evidence examining the development of EEG measures of attention is the reliance on time-domain analyses of the EEG data (i.e., ERP analyses). ERP analyses focus on neural activity time-locked to the auditory stimuli and assume that the component of interest is synchronized in time across trials, ignoring signals that are not synchronized (i.e., non-phase-locked; Luck, 2014). Moreover, ERP analyses do not isolate different frequencies. In contrast, time-frequency analyses separately measure the amplitude and phase of neural oscillations across different frequencies, providing unique information on the neurophysiological mechanisms underlying the EEG data (Cohen, 2014). By separating amplitude and phase information, time frequency analyses are able to isolate the signal strength (power) and the consistency of the oscillations across trials (inter-trial phase synchrony; ITPS) at a specific time and frequency. Time-frequency analyses may provide valuable insight into the neurocognitive processes captured by auditory oddball tasks and the neural mechanisms that change across development. For example, distinct developmental changes in power and phase

synchrony can amplify or mask observed changes in the magnitude of an ERP component (DuPuis et al., 2015; Gavin et al., 2019; Morales & Bowers, 2022). This can lead to developmental changes that are only observable when using time-frequency analyses and not when utilizing ERPs (Bowers et al., 2018, 2021; Morales et al., 2022).

Time-frequency studies of auditory attention suggest that power and inter-trial phase synchrony (ITPS) within the theta frequency band (~4–8 Hz) are heavily implicated in novelty detection and attention orienting (Bishop, Hardiman, et al., 2011; Fuentemilla et al., 2006, 2008; Isler et al., 2012; Müller et al., 2009). Frontocentral theta oscillations are increased in response to novelty and often interpreted as involving several higher-level cognitive functions like attention orienting, active learning, and cognitive control (Bergus & Bonawitz, 2020; Cavanagh & Frank, 2014; Narayanan et al., 2013). Frontocentral theta has especially been studied in the context of cognitive control, in which these oscillations are conceptualized as a signal in response to a prediction error indicating the need for top-down control. Moreover, theta oscillations are thought to be the mechanism by which top-down control is instantiated (Cavanagh & Frank, 2014; Verguts, 2017); thus, it is possible that the theta oscillations elicited by auditory prediction errors are associated with top-down control.

The few studies examining the development of attention using auditory oddball paradigms with time-frequency approaches suggest that frontocentral theta power and ITPS increase in response to deviant tones and that this difference tends to increase with age (Bishop, Anderson, et al., 2011; Bishop, Hardiman, et al., 2011; Müller et al., 2009). Importantly, all the existing time-frequency evidence comes from two-stimulus oddball tasks, which are thought to be ideally suited to examine change-detection processes. To our knowledge, previous time-frequency studies have not included any complex or highly novel sounds considered to index attention orienting. In addition, all studies have focused on school-aged children (7 years) or older. Consequently, age-related changes in these EEG measures of attention during earlier developmental periods are currently unknown.

## 1.3 | Associations to behavior

In addition to characterizing neural responses in a more comprehensive manner by examining ERP and time frequency responses, investigating how these electrophysiological measures of attention relate to behavior would further clarify if the processes captured by these tasks are associated with top-down attention processes. As described above, emerging evidence suggests that there is

important overlap in the brain networks implicated in bottom-up and top-down auditory attention (Alho et al., 2015; Barceló et al., 2002, 2006; Huang & Elhilali, 2020; Salmi et al., 2009). This has led to the hypothesis that top-down changes in behavior (e.g., rule changes during a task) activate a common neural network with bottom-up attention involved in novelty processing and attention orienting (Barceló et al., 2002, 2006). Data supporting this hypothesis have exclusively come from complex tasks with adults involving goal-directed attention shifting by using auditory cues (e.g., Barceló et al., 2002, 2006). The few studies with children examining the relations between electrophysiological responses to auditory novelty have focused on relations with behavioral measures of perceptual discrimination between sounds (Bishop, Hardiman, et al., 2011). For example, Bishop and colleagues found that increased signal consistency in the theta band predicted improved (i.e., more developed) threshold discrimination between tones. However, to our knowledge, no studies have examined the relations between EEG measures of auditory attention and behavioral tasks involving top-down control. Inhibitory control is the ability to suppress a dominant response in a top-down or intentional manner (Nigg, 2017). Thus, examining if EEG measures of auditory detection and attentional capture are related to inhibitory control would provide evidence for their relation to higher-order attention processes involving top-down attention.

## 1.4 | Current study

In the current study, we applied ERP and time-frequency approaches to data collected from a three-stimulus oddball paradigm in a large sample of children to better understand the different forms of attention involved in detecting and attending to novel auditory stimuli. We examined the development of the ERPs (MMN, LDN, P3a), power, and phase consistency (ITPS) in the theta band across childhood in a large sample of children from 4–11 years-of-age. Although most studies have focused on neuronal oscillations in the theta frequency range, neuronal activity in the delta frequency range (<4 Hz) has also been implicated in detection and attention-orienting processes, primarily in work with adults (Bishop, Anderson, et al., 2011; Cavanagh et al., 2009; Isler et al., 2008; Munneke et al., 2015; Prada et al., 2014). Moreover, delta power and ITPS have been found to significantly increase with age across childhood and adolescence (Bowers et al., 2018; Morales et al., 2022). Consequently, in an exploratory analysis, we also investigated oscillations in the delta band.

In the time domain (ERPs), we expected to observe three components: the P3a component in response to novel stimuli and the MMN and LDN in response to deviant

stimuli—all compared to standard stimuli. Based on previous studies, we hypothesized age-related increases in the P3a and MMN and age-related decreases in the LDN. For time-frequency analyses, we expected to observe frontocentral delta/theta power and ITPS responses for both deviant and novel stimuli, but we expected a larger delta/theta response for novel stimuli. We hypothesized that we would observe age-related increases in frontocentral delta/theta power and ITPS responses.

Finally, in order to examine the functional significance of the ERP and time-frequency measures, we tested their association with behavioral measures of inhibitory control. The goal of these analyses was to examine if these electrophysiological measures were associated with behavioral measures of top-down attention, rather than differentiate bottom-up and top-down processes. We hypothesized that delta and theta signal strength (power) and consistency (ITPS) to deviant and novel stimuli would be positively associated with increased inhibitory control because similar delta/theta responses have been observed in cognitive control (Cavanagh et al., 2009; Morales et al., 2022). Moreover, although no study has specifically examined the relations between the ERP measures (P3a, MMN, and LDN) and inhibitory control, studies with adults suggest that conditions that evoke the P3a are associated with behavioral task impairments (i.e., slower RTs and worse performance) on a task-switching paradigm (Barceló et al., 2006). Thus, we expected that the P3a (to novel stimuli) would be negatively associated with inhibitory control. Finally, we did not have any specific hypotheses on how the MMN or LDN would relate to inhibitory control.

## 2 | METHOD

### 2.1 | Participants

Children ( $N = 630$ ;  $M_{\text{age}} = 6.48$  years;  $SD_{\text{age}} = 2.20$ ; 326 female, 304 male) took part in a study examining the impact of early environmental exposures on children's health and neurocognitive outcomes over two data collection sites in South Dakota, USA. Data included in this manuscript were collected between September 2018 and March 2020. More information on the larger study has been previously published (Dukes et al., 2014). As part of the larger study, children were invited to participate in an EEG assessment at one of five assessments based on their age. Assessments were at 4, 5, 7, 9, and 11 years. Of the 616 participants that agreed to complete the EEG portion of the visit, 68 were unable to complete the MMN task, 39 completed the task but were removed due to technical difficulties, and 25 were removed because they did not contain sufficient

trials per condition, yielding a final sample of 475 children (249 female, 226 male;  $M_{\text{age}} = 6.71$ ;  $SD_{\text{age}} = 2.22$ ;  $\text{Range}_{\text{age}} = 4.01\text{--}11.5$  years).

The sample who provided usable EEG data was largely White (81.1%), followed by American Indian (12.0%), and other races (6.9%). Additionally, information regarding the number of participants and their age at each assessment point was as follows: 4 ( $n = 87$ ;  $M_{\text{age}} = 4.23$ ;  $SD_{\text{age}} = 0.17$ ), 5 ( $n = 114$ ;  $M_{\text{age}} = 5.23$ ;  $SD_{\text{age}} = 0.16$ ), 7 ( $n = 153$ ;  $M_{\text{age}} = 7.22$ ;  $SD_{\text{age}} = 0.15$ ), 9 ( $n = 67$ ;  $M_{\text{age}} = 9.25$ ;  $SD_{\text{age}} = 0.13$ ), and 11 ( $n = 54$ ;  $M_{\text{age}} = 11.25$ ;  $SD_{\text{age}} = 0.14$ ). As an indicator of their socioeconomic status, mothers reported on average 14.9 years of education ( $\text{Range} = 7\text{--}17$  years). Children that contributed EEG data did not differ in sex ( $p = .62$ ), but were more likely to be older ( $p < .001$ ), White ( $p < .001$ ), and have more educated mothers ( $p < .001$ ) than children who did not contribute EEG data.

## 2.2 | Protocol/procedure

Prior to data collection, primary caregivers of the participants provided informed consent and children provided assent. Participants were seated about 70 cm from a computer monitor. After EEG cap placement, participants completed a three-stimulus auditory oddball paradigm. Before the oddball task, participants completed a 3-min baseline (not reported here). After the oddball task, children completed a child-friendly Go/No-Go task. The task was presented in E-Prime 2.0.10 (Psychology Software Tools, Pittsburgh, PA). While the three-stimulus auditory oddball paradigm was presented, children watched a silent video with nature scenes in order to maintain their attention. Families were compensated for their participation and children were given a small gift (e.g., toy). The Avera Institutional Review Board approved all study procedures.

## 2.3 | EEG data acquisition

EEG was recorded using a 64-channel HydroCel Geodesic Sensor Net with a Net Amps 400 and sampled at 500 Hz via EGI software (Net Station Version 5.4; Electrical Geodesics, Inc., Eugene, OR). The nets used had the four face channels (61–64) removed to measure other psychophysiological measures (e.g., heart rate). Prior to data collection, impedance values were checked for all EEG channels and confirmed to be below 50 k $\Omega$ . All data were collected with a visual filter of 0.1 Hz and a notch filter of 60 Hz. Moreover, the Cz electrode was used as the reference.

## 2.3.1 | Auditory oddball task

EEG data were acquired during an auditory oddball task. Sounds (200 ms in length; inter-stimulus interval 300 ms) were presented via free-field speakers at  $\sim 75$  dB peak SPL while the child watched a silent video. Each block consisted of 400 sounds ( $\sim 3.5$  min) and was comprised of 3 different types of sounds (standard, deviant, or novel). Standard sounds were simple tones composed of a sine wave of 500 Hz. Deviant sounds were simple tones composed of a sine wave of 650 Hz. The simple tones used for standard and deviant tones were counterbalanced across blocks (i.e., block 1 used 500 Hz tones as standard and 650 Hz tones as deviant and block 2 had the reverse configuration). Novel sounds consisted of complex sounds (e.g., a car horn or a cow mooing). All sounds were obtained from Fabiani et al. (1996). Within each block, 80% of the sounds presented were standard tones, 10% were deviant tones (those that differ from the standard in terms of pitch), and 10% were novel sounds. Each deviant or novel stimulus was preceded by a sequence of 3, 4, or 5 standard stimuli, with the deviant and novel stimuli being presented in a randomized order. This order was the same across participants. In order to control for the effects of previous trials across conditions, we only utilized standard trials that were preceded by at least three other standard trials. Children listened to 2 blocks (800 trials) with a break in between.

## 2.4 | EEG processing

EEG data were processed using a standardized pre- and post-processing pipeline specifically designed for developmental data (MADE; Debnath et al., 2020; Leach et al., 2020). In short, EEG data were exported to Matlab (Mathworks, Natick, MA) for offline processing with EEGLAB (v13.6.5b) toolbox (Delorme & Makeig, 2004) and customized Matlab scripts (Matlab 2014b). Continuous data were high pass filtered at 0.3 Hz and then low pass filtered at 50 Hz. We identified and removed artifact-laden channels using the EEGLAB plugin FASTER (Nolan et al., 2010). To further remove ocular and muscle artifacts, we performed independent component analysis (ICA) on an identical copy of the dataset. Before ICA, this copied dataset was high pass filtered at 1 Hz and segmented into 1 s epochs to improve ICA decomposition. Moreover, noisy segments of the data were rejected using a combined voltage threshold of  $\pm 1000$   $\mu\text{V}$  and spectral threshold (range  $-100$  dB to  $+30$  dB) within the 20–40 Hz frequency band to delete activity likely generated by muscle artifacts. If this artifact rejection process identified an artifact in more than 20% of the epochs

for a given channel, that channel was removed from both the ICA copied data set and the original data set. After running ICA on this copied data set, we applied back the ICA weights to the original data set (Debner et al., 2010). We removed artifactual ICs from the original data set by using the Adjusted-ADJUST algorithm (Leach et al., 2020). We then epoched the data into 1500 millisecond segments that started 500 milliseconds before the sound onset.

After ICA artifact removal and epoching, a two-step procedure for identifying residual artifacts was employed. First, to capture the presence of residual ocular activity not removed through ICA, we rejected any epochs in which ocular channel (1, 5, 10, and 17) voltages exceeded  $\pm 150 \mu\text{V}$ . Second, for any epoch in which non-ocular channel voltages exceeded  $\pm 125 \mu\text{V}$ , we interpolated these channels at the epoch level. However, if more than 10% of the channels (not considering globally rejected channels) exceeded  $\pm 125 \mu\text{V}$ , we rejected the epoch. Finally, we interpolated all missing channels using a spherical spline interpolation and then referenced the data to the average of all the electrodes. The average percentage of interpolated channels per epoch (including those globally rejected) was 4.03% (range 0.3%–18.6%).

The average number of remaining trials included for analysis for each of the three conditions was 141.37 standard ( $SD = 21.55$ ); 70.78 deviant ( $SD = 10.85$ ), and 70.63 novel ( $SD = 11.00$ ). Children with less than 20 trials for any condition were removed from further analysis (see above).

### 2.4.1 | ERPs

ERPs for each child were averaged separately for each condition and baseline-corrected to the average voltage in the 100 ms pre-stimulus period. The time windows and electrode clusters for each ERP component (MMN and P3a) were selected based on previous papers in developmental populations and visual inspection. For all ERPs, we focused on the frontocentral electrode cluster (4, 7, and 54). For the MMN, we focused on 100–200 ms after deviant tones. For the LDN, we focused on 350–500 ms after the deviant tones. For the P3a, we used 150 to 300 ms after the novel tones.

### 2.4.2 | Time-frequency

Time frequency (TF) power and ITPS in each epoch of interest were computed using custom MATLAB scripts (Morales & Bowers, 2022), adapted from Cohen (2014). First, the epoched data were filtered with a surface

Laplacian filter in order to minimize volume conduction over the scalp by filtering out spatially broad features of the data (Cohen, 2014) in order to improve both spatial and functional specificity of brain activity (Tenke & Kayser, 2012). Each Laplacian-filtered epoch was convolved with Morlet wavelets, which estimated spectral power in the frequency range 2–20 Hz (in 60 steps spaced logarithmically). To optimize the time-frequency resolution, wavelet cycles were set at 3 cycles at the lowest frequency (2 Hz) increasing to 10 cycles at the highest frequency (20 Hz).

#### *Power*

Power was computed for all channels and separately for the three conditions (standard, deviant, and novel). Power for each condition was normalized using a (dB) transform ( $\text{dB power} = 10 \times \log_{10} [\text{power}/\text{baseline}]$ ), where the baseline was the average power for each condition from  $-100$  to  $0$  ms before the stimulus onset (Morales & Bowers, 2022).

#### *Inter-trial phase synchrony (ITPS)*

ITPS measures the consistency of the phase oscillations at each timepoint across trials. ITPS values range from 0, indicating random phase at that time point, to 1, representing perfect phase alignment at that time point. ITPS was calculated by calculating the average phase angle across trials for each condition. A subsampling procedure was used to eliminate biases associated with having different numbers of trials per condition (Cohen, 2014). ITPS was calculated for 10 trials that were randomly selected per condition. This subsampling procedure was performed 20 times, then all subsamples were averaged. ITPS was baseline corrected per condition based on  $-100$  to  $0$  ms before stimulus onset. This process created ITPS surfaces per condition with the same dimensions as the TF measures for each electrode for each participant.

## 2.5 | Behavioral inhibitory control

### 2.5.1 | Go/No-go task (Zoo Game)

The Zoo Game is a child-friendly computer-based Go/No-go task (Grammer et al., 2014; Morales et al., 2022). As previously described (Morales et al., 2022), children were told to help a zookeeper catch animals that had escaped from their cages, but not to not catch the orangutan—the zookeeper's assistant helping to catch the animals. Specifically, children were instructed to press a button to catch all of the animals (Go trials) but to withhold responses for the orangutan (No-go trials). To make the task

more developmentally appropriate, there was only one picture of an orangutan at age 4. At the other ages, there were three different pictures of orangutans, all of which served as no-go trials. All other parameters were identical across ages. Children practiced the task until the experimenter believed they understood the task, then completed up to 320 test trials presented in eight blocks of 40 trials each. The task consisted of 75% Go trials and 25% No-go trials. As in previous studies involving RT-based tasks with children (Bowers et al., 2021; Morales et al., 2016), all Go and No-go data were cleaned to remove anticipatory responses (RTs < 150 ms) prior to the computation of accuracy measures. Response accuracy was calculated on both Go and No-go trials. Of the 475 participants with EEG data, 451 children also had data on the Go/No-Go task. Reasons for missing data were children not completing the Go/No-Go task or exclusion for not completing at least 160 trials or not having greater than 60% overall accuracy. Although this cutoff of 60% overall accuracy is relatively liberal, the same cutoff has been previously used (Morales et al., 2020, 2022) and similar or lower thresholds have been used in developmental studies with the same task (e.g., Troller-Renfree et al., 2019). Importantly, sensitivity analyses suggest that changing this cutoff to a more stringent value of 75%, produces the same pattern of results as the ones reported below. Moreover, as in previous studies (Morales et al., 2020), the percent correct on the No-go trials served as the index of inhibitory control, with greater percentage correct indicative of greater inhibitory control.

## 2.6 | Analytic approach

### 2.6.1 | Time-frequency regions of interest selection

The frequencies and time windows of the regions of interest (ROIs) were selected a priori based on previous papers in developmental populations and confirmed with visual inspection. Given our primary interests in different attention processes we focused on delta (2–4 Hz) and theta (4–8 Hz) power and ITPS over the frontocentral electrodes (FCz; 4, 7, and 54). We defined these frequency bands based on previous studies with young children (e.g., Canen & Brooker, 2017; DuPuis et al., 2015; Kikuchi et al., 2011; Morales et al., 2022; Orekhova et al., 2006). To determine the time windows of interest unbiased for condition effects, delta and theta power as well as ITPS were each averaged over all conditions from 0 to 500 ms post stimuli. As expected, we observed a clear delta and theta response between 100–400 ms for power and 0–400 ms for ITPS. Moreover,

examining topographic maps and time-frequency surfaces confirmed these ROIs. Finally, in the supplement we provide time-frequency surfaces at the different ages, showing similar frequency and timing across age, further supporting the use of these ROIs.

### 2.6.2 | Statistical models

In order to examine condition effects and if these effects significantly changed with age, a series of multilevel models (MLMs) were performed using the *nlme* package in R (Pinheiro et al., 2016; R Development Core Team, 2008). Models were performed separately for each outcome of interest; namely, each ERP (P3a, MMN, LDN), power within each frequency band (delta and theta), and ITPS within each frequency band (delta and theta). Models were examined in two steps. In the first step, we included the main effects of age and condition (Standard, Deviant, and Novel) with Standard as the reference condition. In the second step, we included the interaction between Condition and Age (Condition  $\times$  Age). A significant interaction would indicate that the effect of Age varies by Condition. If the Condition-by-Age interaction was not significant, the first model (without the interaction) was interpreted. Moreover, all models controlled for the effects of sex, number of trials in each condition, and data collection site and included the random intercept effect for each participant.

To test the relations between the EEG measures of attention and inhibitory control, we first computed difference scores by subtracting the standard activity (ERP or time frequency) from the average responses to novel and deviant stimuli, separately. We then examined zero-order correlations between all measures. Finally, to more directly test the association, we performed regression models predicting No-Go accuracy while controlling for Go accuracy, number of trials included in the EEG measures, age, sex, and data collection site. This was done in three models: ERPs, time-frequency measures in theta band (power and ITPS), and time-frequency measures in the delta band (power and ITPS). In order to utilize all the available data, these regressions were conducted as path models using full information maximum likelihood estimation (FIML) to account for missing data and reduce potential bias in the parameter estimates (Enders & Bandalos, 2001). This approach allowed for the inclusion of all participants with data on one or more variables (as opposed to list-wise deletion). Moreover, due to the missing data and to correct for any departures from multivariate normality, we used a robust maximum likelihood estimator for these regressions (Yuan & Bentler, 2000).

### 3 | RESULTS

#### 3.1 | ERPs

##### 3.1.1 | P3a

As expected, and shown in [Figure 1](#), we observed a clear P3a component, indexed by an amplitude increase between 150 and 300 ms in frontocentral electrodes in response to novel stimuli, compared to standard stimuli ( $b = 5.40, p < .001$ ). Examining the interaction with age revealed that the P3a response did not change with age ( $b = 0.07, p = .147$ ).

##### 3.1.2 | MMN

As expected, and shown in [Figure 1](#), we observed an MMN component, indexed by a more negative deflection between 100 and 200 ms in frontocentral electrodes in response to deviant stimuli, compared to standard stimuli ( $b = -0.31, p < .001$ ). Examining the interaction with age revealed that the MMN response did not change with age ( $b = -0.01, p = .814$ ).

##### 3.1.3 | LDN

As expected, and shown in [Figure 1](#), we observed the LDN component, indexed by a more negative deflection between 350 and 500 ms in frontocentral electrodes in

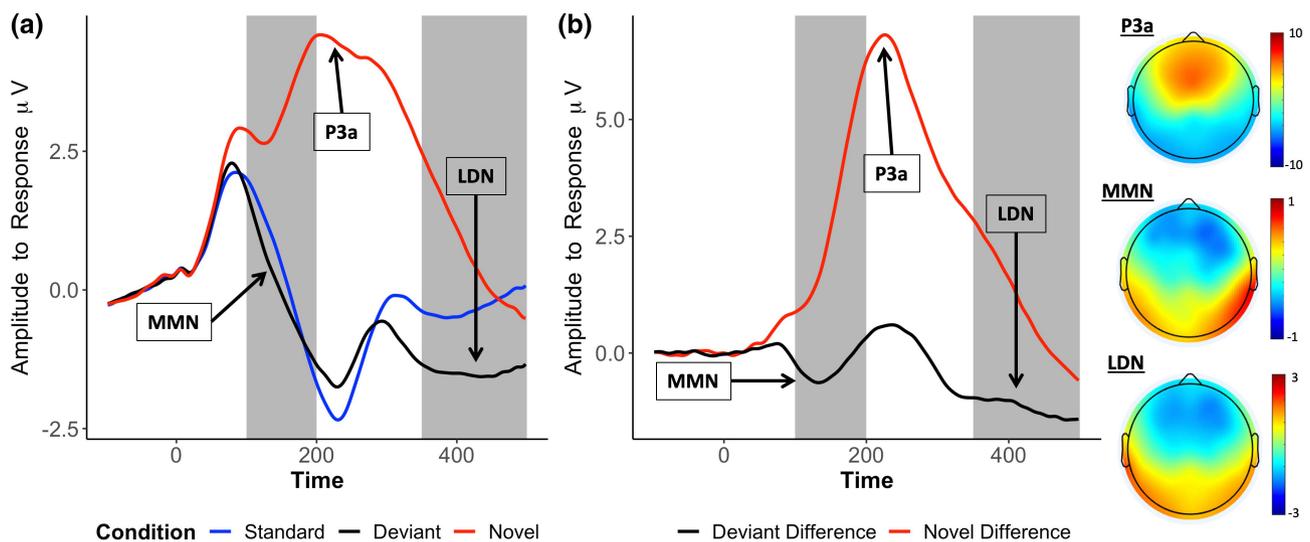
response to deviant stimuli, compared to standard stimuli ( $b = -1.18, p < .001$ ). When adding the interaction with age revealed a significant interaction, such that the LDN significantly decreased in magnitude (i.e., less negative) as age increased ( $b = 0.18, p < .001$ ).

#### 3.2 | Time frequency

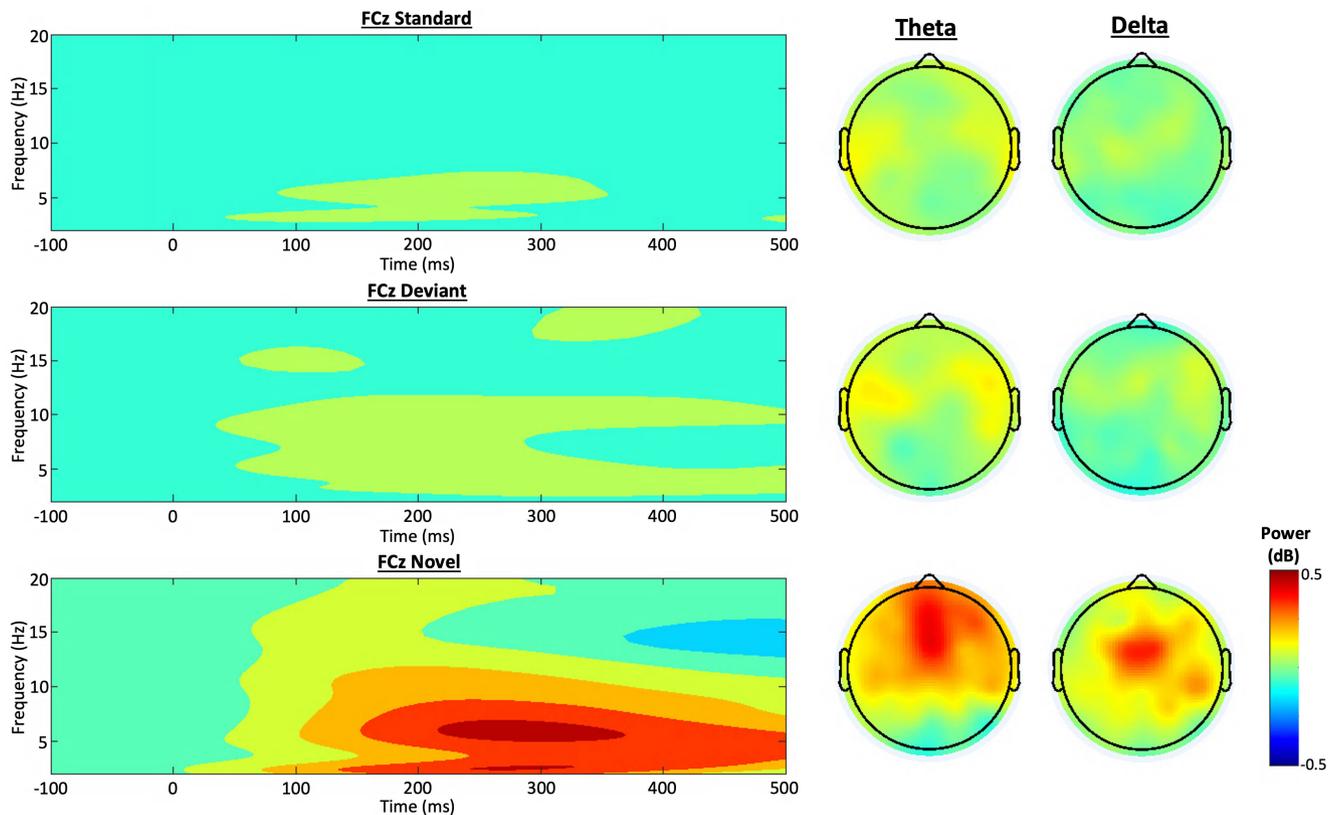
##### 3.2.1 | Power

As expected, and shown in [Figures 2 and 3](#), we observed a significant effect of condition for delta and theta power ( $p < .001$  and  $p < .001$ , respectively). Probing this effect revealed power increases between 100 and 400 ms in frontocentral electrodes in response to novel stimuli, compared to standard stimuli in delta and theta,  $b = 0.35, p < .001$  and  $b = 0.33, p < .001$ , respectively. However, there was no effect in response to deviant stimuli compared to standard stimuli in delta and theta,  $b = 0.03, p = .318$  and  $b = 0.03, p = .245$ , respectively.

When adding the interaction between condition and age, the interaction was significant for delta and theta ( $p < .001$  and  $p < .001$ , respectively). Probing these interactions and as shown in [Figure 3](#), we observed that the response to novelty, compared to standard tones, significantly increased with age for delta and theta ( $b = 0.08, p < .001$  and  $b = 0.06, p < .001$ , respectively). In contrast, we did not observe evidence that the response to deviant stimuli changed with age for delta or theta ( $b = 0.01, p = .367$  and  $b = 0.01, p = .262$ , respectively).



**FIGURE 1** ERP measures: MMN, LDN, and P3a. ERP plots by condition (a) and as a difference score (b; Deviant—Standard and Novel—Standard) for the overall sample labeling the three ERPs elicited by the three-stimulus oddball paradigm. The topography of each of the components (as a difference score) is displayed on the far right.



**FIGURE 2** Time-frequency surfaces of power by condition for frontocentral cluster and topographs for the delta (2–4 Hz) and theta (4–8 Hz) between 100–400 ms.

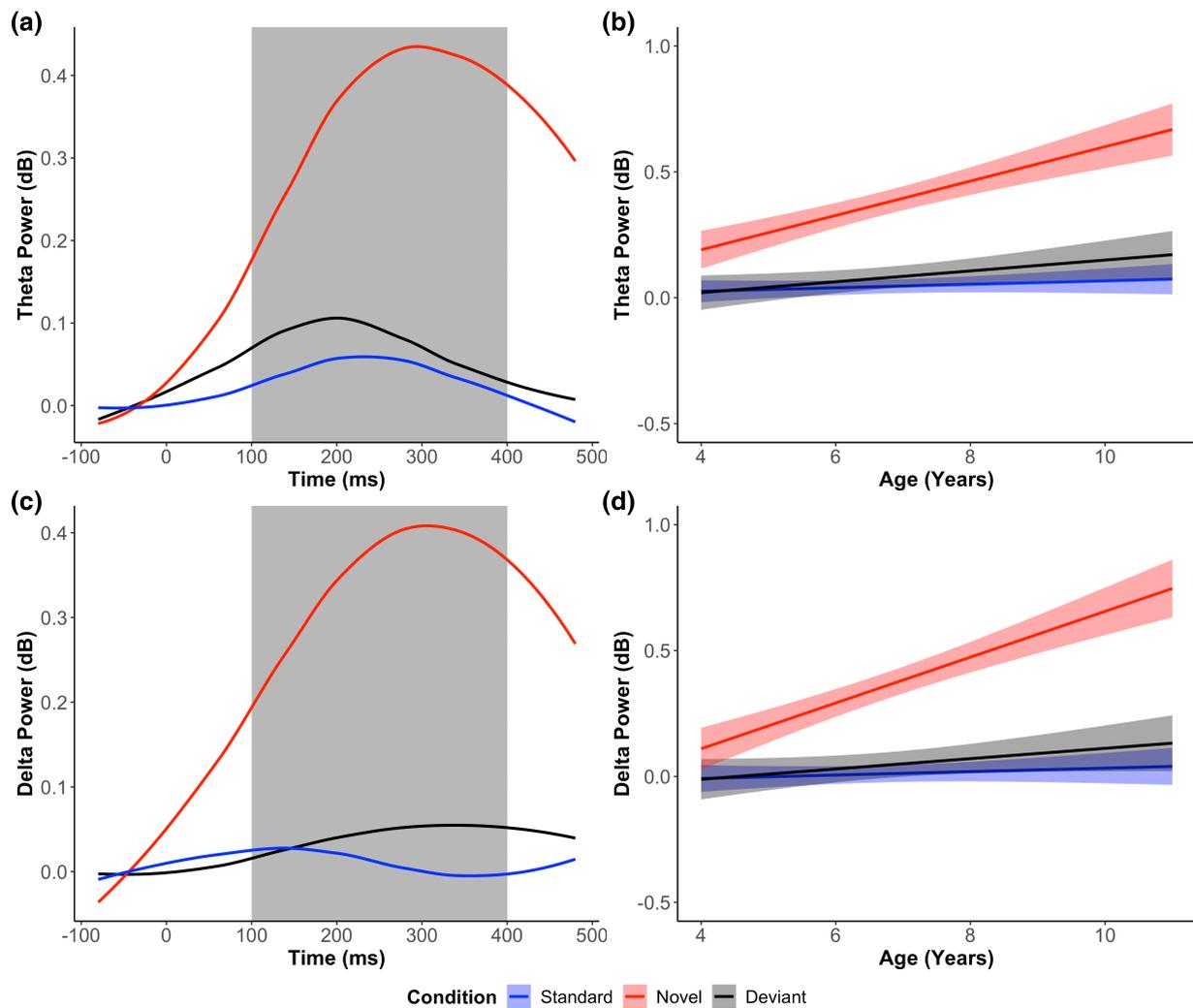
### 3.2.2 | ITPS

As shown in [Figures 4 and 5](#), we observed a significant condition effect for ITPS in delta ( $p < .001$ ). Probing this effect revealed ITPS increases between 0 and 400 ms in frontocentral electrodes in response to novel stimuli, compared to standard stimuli in delta,  $b = 0.023$ ,  $p < .001$ . However, there was no effect in response to deviant stimuli compared to standard stimuli in delta and theta,  $b = -0.001$ ,  $p = .905$ . Moreover, we did not observe a significant condition effect for ITPS in theta ( $p = .052$ ).

When testing the interaction between condition and age, it was significant for delta and theta ( $p < .001$  and  $p < .001$ , respectively). Probing these interactions and as shown in [Figure 5](#), we observed the ITPS response to novelty, compared to standard tones, significantly increased as age increased for delta and theta ( $b = 0.005$ ,  $p < .001$  and  $b = 0.002$ ,  $p = .001$ , respectively). In contrast, we did not observe evidence that the response to deviant stimuli changed with age for delta or theta ( $b < 0.001$ ,  $p = .211$  and  $b = -0.001$ ,  $p = .105$ , respectively).

### 3.3 | Associations to behavior

In order to examine the relations between the EEG attention measures and behavioral measures of inhibitory control, we computed difference scores to better isolate the effects of novel (novel—standard) and deviant (deviant—standard) sounds. As shown in [Table 1](#), correlation analyses revealed that accuracy in Go trials and overall accuracy in the Go/No-Go task was positively related to delta and theta power and ITPS in response to novel sounds. No-Go accuracy was negatively related to P3a amplitude and positively related to delta and theta ITPS. To more directly examine the relations with inhibitory control, we conducted three regressions predicting No-Go performance while controlling for performance in Go accuracy and age, along with other covariates (see above). The regression model including theta time-frequency measures revealed that theta ITPS to novel sounds remained a significant predictor of No-go accuracy ( $b = 64.84$ ,  $\beta = .125$ ,  $p = .006$ ). Both regression models including ERP and time-frequency measures in the delta band, revealed no significant EEG predictors.



**FIGURE 3** Time-frequency dynamics of delta and theta power in response to standard, deviant, and novel sounds. Plots show time-frequency power for each condition across all participants (a, c), age-related changes in time-frequency power in the selected time window (b, d) for each condition.

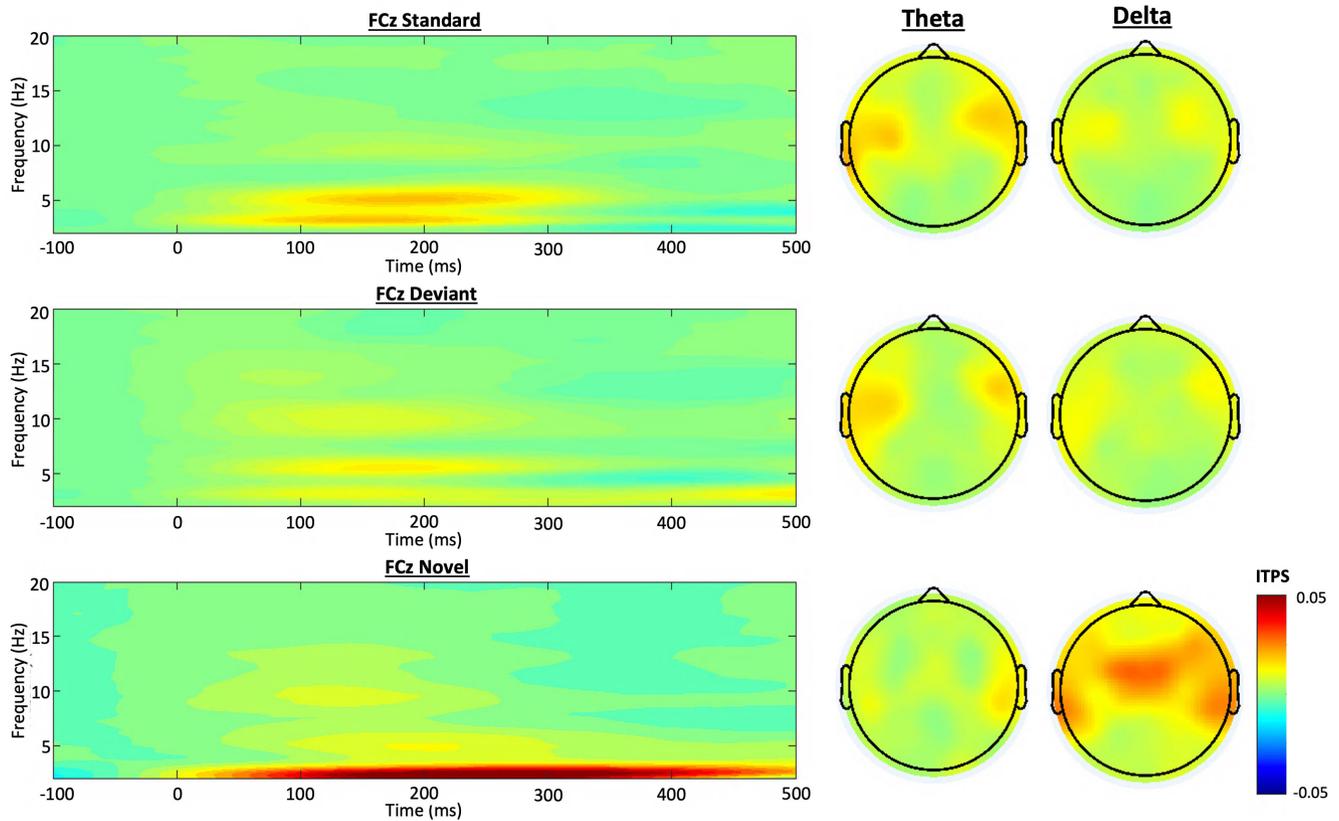
## 4 | DISCUSSION

In the current study, we used EEG and an auditory odd-ball task to examine age-related differences in the auditory attention processes of change-detection and orienting across age. Most previous studies examining the development of these processes have focused on ERP measures, grouped using broad ranges of ages (e.g., 7–12 years vs. adults), and did not examine early childhood (i.e., <7 years). Here, by leveraging a large sample, and ERP as well as time-frequency analyses, we were able to provide a thorough examination of the age-related changes in auditory detection and attention processes across childhood (4 to 11 years). Moreover, we evaluated the relation between these EEG measures of auditory processing and behavioral measures of inhibitory control to better understand if the processes captured by these passive auditory tasks involve higher-order, top-down attention processes.

### 4.1 | ERPs: P3a, MMN, and LDN

When examining the ERPs, our results showed a clear positivity in response to novel sounds in the time window and topography corresponding to the P3a component. However, contrary to our expectations, we did not observe age-related changes in the P3a. Although this is not what we hypothesized, these findings are in line with a recent review, which concluded that the P3a component is present from infancy, remains similar across development, and shows no clear developmental changes in amplitude (Riggins & Scott, 2020). Similarly, our P3a findings suggest that the involuntary attention-orienting response is developed by early childhood and shows little change in amplitude between 4 and 11 years.

In response to deviant sounds, we observed negative deflections in the time windows and topography corresponding to the MMN and LDN components. Unexpectedly, we



**FIGURE 4** Time-frequency surfaces of inter-trials phase synchrony (ITPS) by condition for frontocentral cluster and topographs for the delta (2–4 Hz) and theta (4–8 Hz) between 0–400 ms.

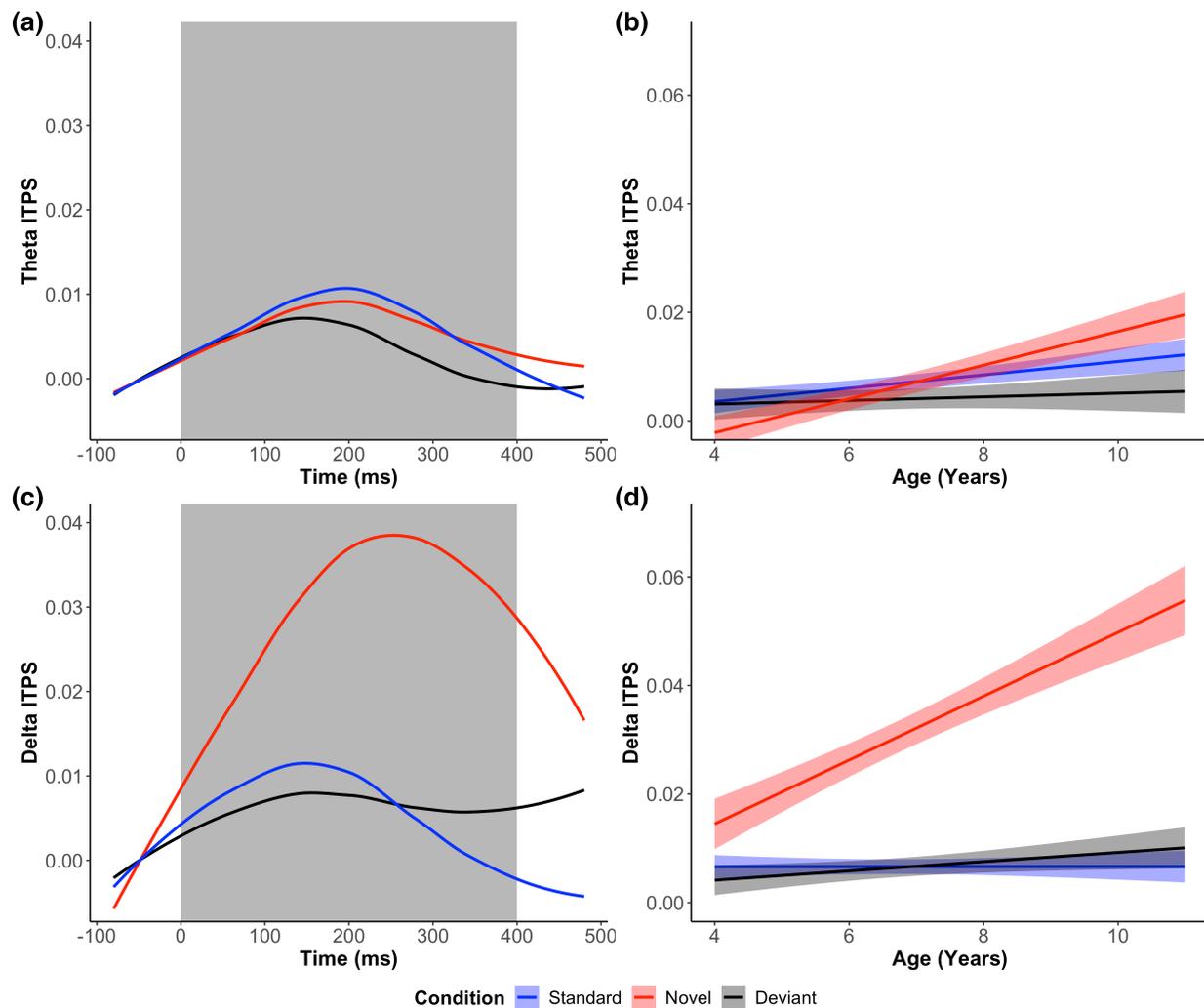
did not observe age-related changes in the MMN. The lack of age-related changes might be due to the age-range that we evaluated. Some of the previous studies finding age-related changes have compared children with adults (e.g., Bishop, Hardiman, et al., 2011). However, our findings are in line with previous studies in that the MMN shows little change across development (Kraus et al., 1999; Shafer et al., 2000), suggesting that the ability to discriminate between sounds is developed and does not change across childhood. When examining developmental changes in the LDN, on the other hand, we observed age-related decreases in this component. These findings are in line with previous studies suggesting that this component decreases with age (Cheour et al., 2001; Kraus et al., 1993). Because the LDN has been interpreted as reflecting increased processing, especially when it is more difficult to distinguish between stimuli (Bishop, Hardiman, et al., 2011), our findings suggest that younger children may engage in further processing when listening to tones—as they may have less experience listening to such sounds.

In sum, although these ERP findings support age-related changes in the LDN, our traditionally analyzed ERP results suggest a lack of age-related changes in the P3a and MMN between ages 4 and 11 years. Therefore, we also conducted time-frequency analyses to further

examine the development of auditory detection and attention processes, which could provide a more nuanced perspective of the developmental changes captured by the EEG.

## 4.2 | Time-frequency analyses

As hypothesized, we observed frontocentral increases in power to novel sounds in delta and theta frequency ranges. These frontocentral delta and theta power increases in response to novel sounds might reflect novelty detection and attention orienting. An extensive literature across development suggests that expectancy violations (e.g., surprising events, or errors) generate frontocentral delta/theta responses, mostly studied as theta-band activity (Begus & Bonawitz, 2020; Buzzell et al., 2019, 2020; Morales et al., 2022). This delta/theta response is likely generated in the anterior cingulate cortex and it is thought to serve as an “alarm” involved in the detection of expectancy violations and prediction error (Cavanagh & Frank, 2014). This theta response plays an important role in higher order processes such as cognitive control and learning (Begus & Bonawitz, 2020; Cavanagh & Frank, 2014). Unexpectedly, we did not observe significant increases in delta or theta



**FIGURE 5** Time-frequency dynamics of delta and theta inter-trial phase synchrony (ITPS) at the FCz cluster in response to standard, deviant, and novel sounds. Plots show ITPS for each condition across all participants (a, c), age-related changes in ITPS in the selected time window (b, d) for each condition.

power in response to deviant tones as previous studies (Bishop, Anderson, et al., 2011; Bishop, Hardiman, et al., 2011; Müller et al., 2009), albeit the nominal direction of effects were in line with prior work. Importantly, previous studies used two-stimulus oddball paradigms without the novel sounds. Moreover, although most studies have shown theta power increases to deviant tones, another study (Bishop, Hardiman, et al., 2011) also did not observe increases in frontocentral theta power to deviant tones in children—it was only observed in adults. This is in line with our findings and suggest that, in the presence of novel tones, deviant tones do not elicit attention orienting, involving frontocentral delta/theta increases like novel sounds in children.

Examining the signal consistency across trials (ITPS), revealed increases in the delta band in response to novel sounds. However, contrary to our predictions, we did not observe, on average, increases in theta ITPS in response to

novel or deviant tones. Previous studies with older children and adults have shown increases in phase synchrony in the theta band (Bishop, Hardiman, et al., 2011), but to our knowledge, none of the previous studies examined these responses in children under 7 years. Thus, it is possible that increased theta ITPS is only observed later in development. This is in line with studies with other forms of prediction error like action monitoring and feedback processing, such that increased consistency in theta is not observed in children (Morales et al., 2022), but emerges later in adolescence (Bowers et al., 2018; Crowley et al., 2014). In support of this interpretation, we found that both the strength (power) and consistency (ITPS) of the delta/theta response following novel sounds significantly increased with age. This suggests important developmental changes in novelty detection and attention orienting across childhood. In contrast, we did not observe developmental changes in delta or theta in strength or consistency in response to deviant tones. Again, this

TABLE 1 Means, standard deviations, and correlations

Variable	N	M	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Sex	475	+																
2. Age	475	6.71	2.22	-.05														
3. Go Accuracy	451	0.92	0.09	-.01	.61*													
4. No-Go Accuracy	451	0.71	0.14	.23*	.24*	.18*												
5. Overall Accuracy	451	0.86	0.08	.09	.61*	.91*	.57*											
6. P3a	475	5.40	2.72	-.28*	.06	.08	-.10*	.03										
7. MMN	475	-0.31	1.58	.06	-.01	-.01	.03	.00	.18*									
8. LDN	475	-1.18	1.99	-.01	.20*	.06	-.02	.04	.14*	.45*								
9. Novel Delta Power	475	0.35	0.79	-.09	.24*	.19*	.04	.17*	.14*	.03	.09							
10. Deviant Delta Power	475	0.03	0.74	-.05	.04	.01	-.02	.00	.02	.04	.11*	.45*						
11. Novel Theta Power	475	0.33	0.64	-.14*	.21*	.19*	-.04	.14*	.15*	-.04	.05	.55*	.33*					
12. Deviant Theta Power	475	0.03	0.60	-.07	.05	-.04	.00	-.03	.05	-.02	.01	.22*	.51*	.39*				
13. Novel Delta ITPS	475	0.02	0.04	-.09	.34*	.23*	.13*	.25*	.32*	-.03	.04	.30*	.06	.28*	.09			
14. Deviant Delta ITPS	475	-0.00	0.02	-.03	.08	.05	.02	.06	.04	-.10*	-.06	.11*	.11*	.09*	.05	.32*		
15. Novel Theta ITPS	475	-0.00	0.03	-.08	.16*	.12*	.13*	.16*	.01	-.03	.06	.10*	-.02	.14*	.04	.26*	.09*	
16. Deviant Theta ITPS	475	-0.00	0.02	-.04	-.08	.01	-.03	-.00	-.02	-.12*	-.03	.01	.02	.04	.01	-.02	.26*	.34*

Note: *M* and *SD* are used to represent mean and standard deviation, respectively. \* indicates  $p < .05$ . +1 = Female and 0 = Males. All the EEG measures are difference scores to isolate the effects of novel (novel-standard) and deviant (deviant-standard) sounds.

implies that, regardless of age, deviant tones do not elicit an orienting response that involves frontocentral delta/theta increases as with novel sounds. It is possible that using other types of deviant stimuli (e.g., language phonemes or syllables), rather than simple tones, would elicit a delta/theta response that would increase with age. Another possibility is that having three different conditions, including the novel sounds, changes the responses to simple deviant tones. Future studies examining different sound and tasks configurations should investigate these possibilities.

Together, our findings showing developmental increases in frontocentral signal strength and consistency in delta and theta bands in response to novel stimuli, raise the interesting possibility that these time-frequency measures are capturing neurocognitive processes related to top-down attentional processes. For example, activity in the theta band has been implicated in self-guided attention from early development (Wass et al., 2018). Similarly increases in frontocentral delta/theta have been observed in performance monitoring, which is an important component of cognitive control (Buzzell et al., 2019; DuPuis et al., 2015; Morales et al., 2022). Thus, we were interested in evaluating if these EEG measures were related to behavioral measures of top-down cognitive processes like inhibitory control.

### 4.3 | Associations with inhibitory control

As expected, our results involving correlations showed a negative correlation between the P3a and inhibitory control. This is in line with experimental adult studies, in which conditions that elicit the P3a are associated with behavioral task impairments (i.e., slower RTs and worse performance) on task-switching (Barceló et al., 2006). Moreover, albeit indirectly, this finding is also in agreement with adult studies in which the P3a is related to personality traits related to impulsivity and ADHD (Gumenyuk et al., 2005; Gurrera et al., 2001, 2005). However, this relation did not survive when controlling for covariates such as age and sex. Moreover, as expected, we also observed a positive relation between inhibitory control and delta and theta ITPS. However, only the relation with theta ITPS survived after controlling for covariates. Previous developmental studies have highlighted the role of theta consistency in the development of neurocognitive processes associated with inhibitory control like error monitoring (DuPuis et al., 2015; Gavin et al., 2019). Together these findings suggest that higher temporal consistency of the signal in the theta band is reflective of more mature and efficient neural systems, supporting attention processes like cognitive

control. To our knowledge, this is the first report of theta consistency being associated with inhibitory control performance as measured in a separate task. This provides further support for the involvement of these signals in top-down attention processes like inhibitory control, even when these theta responses are elicited by a different modality (i.e., auditory). Our results are in line with previous experimental evidence from adults that suggests that bottom-up and top-down auditory attention systems may rely on a common brain network (Alho et al., 2015; Barceló et al., 2002, 2006; Huang & Elhilali, 2020; Salmi et al., 2009). Moreover, it suggests that similar tasks that have low cognitive and motor demands could be used to examine the development of some attention processes from early in development, starting in infancy.

### 4.4 | Limitations and future directions

The findings of the current study should be considered in light of several limitations. First, this was a cross-sectional study with relatively tight age ranges around each age (i.e., 4, 5, 7, 9, and 11 years). Future studies should utilize longitudinal designs to be able to measure within-person changes and include a wider and continuous age range. Another major limitation was that we had missing data due to compliance or technical errors. Even though the number of participants lost due to insufficient trials was low (<5%), compared to other paradigms with higher cognitive and motor demands (e.g., Morales et al., 2022), our analyses examining factors associated with missing data still indicated that missing data did not occur at random. Missing data were more likely to occur for younger participants, non-White participants, and those with low levels of maternal education. This highlights the need for improved practices to facilitate the participation and retention of families from underrepresented backgrounds that are in addition to paradigms that increase the amount of artifact free data. For example, future studies could improve on how EEG is introduced to families, reducing the study burden, as well as creating and using hardware that facilitates EEG recordings with a diverse set of hair types (Etienne et al., n.d.). Finally, although we report the relations between EEG measures, the current study examined each of their relations with inhibitory control mostly independent from each other. We encourage future studies to investigate the relations between EEG measures in a multivariate model to better understand the temporal relations between measures (e.g., Lin et al., 2022) or by examining profiles of children with unique patterns across EEG measures.

## 5 | CONCLUSION

EEG methods offer a promising approach to study the development of attention or attention-related processes such as change-detection and attentional capture. In the current study, we utilized a passive three-stimulus odd-ball paradigm to examine age-related changes in auditory change-detection and attentional capture across early childhood. Conventional ERP analyses revealed age-related reductions in the LDN, but no developmental changes in the MMN and P3a components. However, we observed developmental increases in frontocentral signal strength (power) and consistency (ITPS) in delta and theta bands in response to novel stimuli. Similar frontocentral delta/theta responses have been involved in higher-order attentional processes like cognitive control, suggesting that these responses to auditory novelty might be related to such top-down processes. This was further supported by examining the relations of these measures to auditory novelty with inhibitory control. Our findings suggest that increased consistency in theta in response to novel sounds is related to improved inhibitory control. Together, our results advance our understanding of the development of attention in childhood and demonstrate the contributions of time-frequency approaches to studying neurocognitive development. Moreover, our results highlight the utility of neuroimaging paradigms that have low cognitive and motor demands to study the development of psychological processes.

### AUTHOR CONTRIBUTIONS

**Santiago Morales:** Conceptualization; data curation; formal analysis; methodology; project administration; visualization; writing – original draft; writing – review and editing. **Maureen E. Bowers:** Conceptualization; methodology; writing – review and editing. **Stephanie C. Leach:** Data curation; methodology; writing – review and editing. **George A. Buzzell:** Writing – review and editing. **Marco McSweeney:** Writing – review and editing. **Lydia Yoder:** Data curation; writing – review and editing. **William Fifer:** Funding acquisition; writing – review and editing. **Amy J. Elliott:** Funding acquisition; supervision; writing – review and editing. **Nathan A. Fox:** Funding acquisition; supervision; writing – review and editing.

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### CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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