

Auditory attention in childhood and adolescence: An event-related potential study of spatial selective attention to one of two simultaneous stories



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ABSTRACT

Auditory selective attention is a critical skill for goal-directed behavior, especially where noisy distractions may impede focusing attention. To better understand the developmental trajectory of auditory spatial selective attention in an acoustically complex environment, in the current study we measured auditory event-related potentials (ERPs) across five age groups: 3–5 years; 10 years; 13 years; 16 years; and young adults. Using a naturalistic dichotic listening paradigm, we characterized the ERP morphology for nonlinguistic and linguistic auditory probes embedded in attended and unattended stories. We documented robust maturational changes in auditory evoked potentials that were specific to the types of probes. Furthermore, we found a remarkable interplay between age and attention-modulation of auditory evoked potentials in terms of morphology and latency from the early years of childhood through young adulthood. The results are consistent with the view that attention can operate across age groups by modulating the amplitude of maturing auditory early-latency evoked potentials or by invoking later endogenous attention processes. Development of these processes is not uniform for probes with different acoustic properties within our acoustically dense speech-based dichotic listening task. In light of the developmental differences we demonstrate, researchers conducting future attention studies of children and adolescents should be wary of combining analyses across diverse ages.

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1. Introduction

Selective attention, the ability to enhance the processing of certain stimuli while suppressing the information from other concurrent stimuli, is critical for regulating external sensory input and occurs within and across sensory modalities (e.g. visual: Çukur et al., 2013, somatosensory: Forster et al., 2009, intermodal: Karns and Knight, 2009, and auditory: Woods et al., 2009). This cognitive ability is fundamental for academic success (Blair and Razza, 2007; Rueda et al., 2010; reviewed in Stevens and Bavelier, 2012). Auditory attention in particular is highly relevant to a school setting in which instruction and completion of assignments may occur in an acoustically noisy environment with competing speech streams. Additionally, the enhancement and suppression of sensory stimulation are disrupted in many children with developmental disorders, including individuals with autism (Reinvall et al., 2013), attention-deficit disorder (Gomes et al., 2013), at-risk readers (Stevens et al.,

2013), dyslexia (Johnson et al., 2013; Stefanics et al., 2011), language impairment (Stevens et al., 2008), deafness (Dye and Hauser, 2013), and non-disordered special populations such as children of lower socioeconomic status (D'Angiulli et al., 2008; Stevens et al., 2009). Selective attention is also key to general processes of neuroplasticity (Neville and Lawson, 1987; Röder et al., 1999; Stevens and Neville, 2006) and understanding the typical developmental trajectory of attention is critical to establish and evaluate the immediate and long-term outcomes of attention-training interventions for children and adolescents (Diamond and Lee, 2011; Neville et al., 2013; Shonkoff, 2011).

The neural indices of selective auditory attention have been extensively studied in adults using dichotic listening paradigms (for a review, see Hopfinger et al., 2004). In adults, event-related potential (ERP) studies with dichotic listening paradigms indicate that spatial auditory selective attention typically modulates the amplitude of neural response to an attended stimulus at the N1 latency (Hillyard et al., 1973; Hillyard, 1981), an increase that could also reflect changes to signal to noise such as increased temporal consistency (Thornton et al., 2007). Attention modulation can also have scalp topographies that are distinct from the sensory

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ERP responses; these are thought to index additional endogenous processing of attended stimuli (Hansen and Hillyard, 1980). Attention modulation can occur as early as 50 ms under certain experimental conditions (Giuliano et al., 2014; Woldorff et al., 1987; Woldorff and Hillyard, 1991) and with intermodal selective attention (Karns and Knight, 2009). This early-latency modulation is consistent with primary cortical processing (Deiber et al., 1988; Liégeois-Chauvel et al., 1994; Woods et al., 1995) and scalp topographies and source modeling of early-latency attention modulations are consistent with sources in the temporal auditory cortices (Weisser et al., 2001; Woldorff et al., 1993). This modification of early sensory processing likely relies upon slowly-developing substrates of distributed cortical attention networks such as the frontal cortex (Knight et al., 1989). One way to view early latency amplitude modulation of ERPs is that the frontal cortex and other brain systems supporting attention hold sensory cortex in a state that is more receptive to processing the attended stimuli than unattended (Karns and Knight, 2009).

ERP studies have demonstrated that the ability to direct auditory spatial attention is evident in the early years of childhood at adult-like latencies of 100 ms (Coch et al., 2005; Sanders et al., 2006) but studies in other domains highlight the limits of child attention. Behavioral studies using dichotic listening tasks have indicated that children have less effective selection abilities (Geffen and Sexton, 1978; Hiscock and Kinsbourne, 1980; Takio et al., 2009) and ERP studies using target-detection paradigms have indicated that both 9- and 12-year-olds show latency, amplitude, and behavioral differences relative to adults (Gomes et al., 2007). Similarly, in a dichotic listening task that required attending to either specific pitch ranges or syllables to detect deviant targets, developmental differences in the neurophysiology of selective attention were observed between children, young adolescents, and adults, but only after 200 ms (Berman and Friedman, 1995). Likewise, in an auditory oddball paradigm with 9–12 year-old children, younger adults, and older adults, age-related differences were reported for the peak latency, peak amplitude, and scalp distribution of components related to selective auditory attention (Mueller et al., 2008). In older children (ages 9–12) there is also evidence that task-relevance shapes complex auditory scene analysis (Sussman and Steinschneider, 2009) but unfortunately the requirement of an overt response by participants limits the age-range for such tasks to older children. In very young children, engaging tasks that manipulate attention without an overt response are particularly important and also allow comparison to older age groups.

Although we have successfully used our naturalistic story-based dichotic listening task to record ERP markers of selective auditory attention in typically-developing children (Coch et al., 2005; Sanders et al., 2006), in clinical and at-risk populations (Stevens et al., 2006, 2008, 2012, 2013), and in children of lower socioeconomic status (Neville et al., 2013; Stevens et al., 2009, 2014), these previous studies did not include adolescents, and there is ample evidence indicating that systems that support attention, such as the frontal and parietal cortices, continue to mature throughout early adolescence (e.g. Berman and Friedman, 1995; Gomes et al., 2007; Mueller et al., 2008; for a review see Segalowitz et al., 2010). To our knowledge, there has been little work that included older adolescents as a potentially distinct age group, and tracked the development of auditory attention from early childhood into adulthood using the same ERP task. Because of the slower developmental timescale of the frontal-parietal attention network (Yurgelun-Todd, 2007) it is highly likely that spatial attentional selection also continues to mature in this older age range.

In studies of children and adolescents across a broad age range, it is important to interpret developmental changes in attention in the context of the continuing development of the auditory system and frontal cortex. While the auditory brainstem forms early

and is myelinated by 37 weeks gestation (Eggermont, 1988) most synapses in the cerebral cortex form after birth, occurring concurrently with growth of dendrites and axons, and myelination of subcortical white matter. Synaptic density peaks in infancy and early childhood followed by pruning through late childhood and adolescence. This occurs on different timescales in the auditory and frontal cortices. In the auditory cortex, synaptic density is maximal at 3 months of age in contrast to 15 months for frontal cortex. Synapse elimination is complete by 12 years of age for the auditory cortex, but continues into mid-adolescence for frontal cortex (Huttenlocher and Dabholkar, 1997) highlighting the non-uniform nature of cortical development in different brain systems.

Given the dynamic process of synaptic growth and pruning occurring across development, it is not surprising that there are striking developmental changes in the morphology of the auditory evoked potentials, which reflect inhibitory and excitatory post-synaptic electrical potentials, from childhood to adulthood. In particular, the P1–N1 complex shows a prolonged developmental time course (Ponton et al., 2000), with the N1 developing later and maturing more slowly than the P1, and a reduction of age-related changes in the later latency P2 and N2 components (Ponton et al., 2002). Despite maturational changes in auditory evoked potentials observed at the scalp, dipole source modeling suggests that the orientations of the generators for the P1–N1–P2–N2 complex are adult-like by 5 years of age (Ponton et al., 2002). In a dichotic listening task with simultaneous stories presented with the story on one side attended, the typical adult response to a brief auditory probe is a P1–N1–P2 complex at the same latency – or for linguistic probes a P1 followed by a later N1. Meanwhile, for young children (3–8 years old) auditory evoked potentials consist of a broad initial positivity from 100 to 300 ms that is modulated by attention (Coch et al., 2005; Sanders et al., 2006). While a negative-going attention modulation at the N1 is the prototypical spatial attention effect in adults (i.e., Hink and Hillyard, 1976), we have recently shown that attention can instead modulate the adult P1 in a linguistic dichotic listening task (Giuliano et al., 2014). Previous researchers have noted that the ability to select among competing stimuli, enhancing the processing of the task-relevant information, is available in very young children, but that the processing speed and efficiency may be what improves as children develop (Ridderinkhof and van der Stelt, 2000) so this very early P1 mechanism of attention modulation might not yet be available to younger children or adolescents.

We undertook the present study to determine how auditory selective attention changes across childhood and adolescence. At first glance, a positive attention effect in young children and a negative attention effect in adults might be construed as a possible polarity reversal of an attention related component superimposed on the auditory evoked potentials. However, an alternative explanation is an attention process that operates as a gain-control mechanism of the auditory evoked potentials, changing the amplitude of the developing auditory evoked potentials such as the P1 and N1. The latency at which this mechanism can operate may develop over the course of childhood and adolescence as underlying cortical systems mature. Our hypothesis in light of previous studies (Sanders et al., 2006; Coch et al., 2005) was that attention modulation at early-latencies, from childhood through adolescence, is best understood as a gain-control modulation of maturing auditory evoked potentials. Furthermore, additional sustained and likely endogenous attention-related processes that are typically deployed at later latencies may also be engaged differentially as neural systems mature. We anticipated, based on previous work with 6–8 year olds that additional sustained processes may distinguish different age groups at later latencies in the 300–450 ms time range (Coch et al., 2005; Sanders et al., 2006). We used a naturalistic dichotic listening task with simultaneously presented

stories that is engaging for preschool aged children, school-aged children, adolescents, and adults to investigate the maturation of selective auditory attention in a cross-sectional sample. The task does not require overt responses; participants simply attended to one of two simultaneously presented stories, and we measured and compared the ERP responses elicited by the same probes when they were presented from the attended stories versus the unattended stories.

2. Methods

2.1. Participants

A cross-sectional sample of children and adults was recruited and paid for participation. Our participant sample consisted of twenty children ages 3.5–5 years (3–5-year-olds), nineteen 10-year-olds, eighteen 13-year-olds, eighteen 16-year-olds, and twenty young adults (18–26-years-old). Children and adolescents were recruited from the Developmental Database of the University of Oregon and pre-screened by telephone to exclude low maternal education to be comparable to a typical adult sample recruited from university settings as well as a comparison group for future studies investigating the effects of socioeconomic status on the development of attention (e.g. [Neville et al., 2013](#)). Adult participants were undergraduate students. All participants were right-handed, monolingual English speakers, with normal or corrected-to-normal vision, and no history of neurological impairment. As shown in [Table 1](#), differences in maternal education between age groups were not significant, although the youngest and oldest age groups tended to be slightly higher ($F(4,87) = 2.41, p = .06$).

2.2. Materials

2.2.1. Auditory selective attention task

As shown in [Fig. 1](#), we used the same spatial selective auditory attention ERP paradigm as our previous studies with children ages 3–8 and adults ([Coch et al., 2005](#); [Neville et al., 2013](#); [Sanders et al., 2006](#); [Stevens et al., 2009](#)). Briefly, participants were cued to selectively attend to one of two simultaneously presented children's stories differing in location (left/right loudspeaker), narrator's voice (a male or female reading the entire story aloud), and content. Illustrations from the story being read from the attended loudspeaker were presented on a monitor. A green arrow pointing to the left or right was displayed throughout each block to indicate the attended side.

ERPs were recorded to 100 ms duration probe stimuli embedded in both attended and unattended stories. Probe stimuli were either linguistic (a voiced syllable) or nonlinguistic (a broad spectrum buzz). The linguistic probe was the syllable /ba/, spoken by a female (a different voice from all the story narrators). The nonlinguistic probe was created by scrambling 4–6 ms segments of the /ba/ stimulus, which preserved many of the acoustic properties of the linguistic probe. Across the stories, approximately 200 linguistic and 200 nonlinguistic probes were presented in each channel. The probes were presented randomly at an inter-stimulus interval (ISI) of either 200, 500, or 1000 ms in one of the two loudspeakers at a time. The stories were presented at an average of 60 dB SPL (A-weighted) and the intensity of the probes was 70 dB. A researcher sat next to children 10 years-old and younger to ensure that they remained still and equidistant between the two loudspeakers, and to administer comprehension questions following each pair of simultaneously presented stories. Older participants were monitored via a video camera and intercom and also answered comprehension questions at the completion of each pair of simultaneously presented stories.

Within their testing session, a total of eight different stories were presented. Since two stories were presented simultaneously, there were a total of four listening blocks. The stories were selected from the following children's book series: Blue Kangaroo ([Clark, 1998, 2000, 2002, 2003](#)), Harry the Dog ([Zion and Graham, 1956, 1960, 1965, 1976](#)), Max & Ruby ([Wells, 1997, 2000, 2002, 2004](#)), and Munsch for Kids ([Munsch and Martchenko, 1989, 2001, 2002](#); [Munsch and Suomalainen, 1995](#)). In each of the four blocks, two stories were presented simultaneously with attention directed to the story played from either the left or right loudspeaker and read aloud by a different narrator from four narrators in total. For a concrete example, in one block, a participant could be directed to listen to the left loudspeaker, which might play a story read by a female narrator, while ignoring the right loudspeaker, which would be playing a story read by a male narrator; the illustrations on the monitor would correspond to the to-be-attended story. Each participant attended twice to the story on the right side and twice to the story on the left side, with start side counterbalanced across participants. For each participant, an individual narrator would be heard once as the narrator for an attended story and once as the narrator for an unattended story.

After each story, an experimenter asked the participant three basic comprehension questions about the attended story to reinforce the goal of paying attention. The comprehension questions always had two alternatives. A response of "I don't know" was counted as an incorrect response. As a criterion for inclusion in data analysis, participants answered a minimum of seven out of 12 questions correctly (58% accuracy). A one-way ANOVA was performed to test for age differences in comprehension question accuracy, revealing lower accuracy in 3–5-year-olds (percent correct = 80%, SD = 11; $F(4,80) = 19.01, p < .001$), but no significant differences in accuracy between the remaining four age groups (10-year-olds, percent correct = 99%, SD = 3; 13-year-olds, 95%, SD = 6; 16-year-olds, 97%, SD = 8; adults, 95%, SD = 8; $F(3,61) = 1.21, p = .32$). Nine adult participants were not asked comprehension questions because of an omission in the testing protocol.

2.2.2. EEG procedures

2.2.2.1. Recording.

Electroencephalogram (EEG) was recorded during the story task at a sampling rate of 512 Hz from 32 Ag/Ag-Cl-tipped scalp electrodes (BioSemi Active2, Amsterdam, Netherlands) arranged according to the international 10–20 system. Electrode offsets were maintained within $\pm 30 \mu\text{V}$ throughout each recording session. Electrodes were also placed horizontally next to each eye and beneath the right eye in order to monitor eye movements and blinks. The EEG was recorded relative to the Common Mode Sense (CMS) active electrode, and then referenced offline to the algebraic mean of the left and right mastoids. Eye movements were monitored via bipolar ocular channels (Vertical eye movements: lower right eye electrode minus electrode Fp1, the right anterior-most site. Horizontal eye movements: right minus left horizontal eye electrodes).

2.2.2.2. Measurement.

ERP analyses were carried out using EEGLAB ([Delorme and Makeig, 2004](#)) and ERPLAB ([Lopez-Calderon and Luck, 2014](#)). Raw EEG data were imported into EEGLAB and the continuous data were high-pass filtered using a two-way, zero phase-lag, finite impulse response filter (`eegfilt` function) to prevent phase distortion; the filter order was three times the sampling rate (512 Hz) divided by the low-frequency cutoff of the filter (.1 Hz), rounded down. For each probe embedded in the story task, epochs were extracted from –100 to 500 ms relative to probe onset. Epochs containing large voltage deviations or muscle/movement artifacts were identified by visual inspection and excluded from further analysis. Remaining data were then submitted to artifact rejection procedures within ERPLAB. Artifacts were identified

Table 1
Maternal education by age group.

Age group	Mean age (SD)	N	Maternal education	S.E.M.
3.5–5	4.8 (.6)	20 (10 F)	6.1	.12
10	10.7 (.5)	18 ^a (9 F)	5.6	.20
13	13.4 (.2)	18 (9 F)	5.7	.23
16	16.6 (.3)	17 ^a (9 F)	5.4	.26
18–26	21.4 (1.8)	15 ^a (8 F)	6.2	.26

Maternal education was coded as Highschool diploma=4, Bachelor's degree=5, Master's degree=6, Doctorate=7. Differences between age groups were not significant ($p > .05$).

^a Maternal education was missing for one 10-year-old, one 16-year-old, and five undergraduate adults.

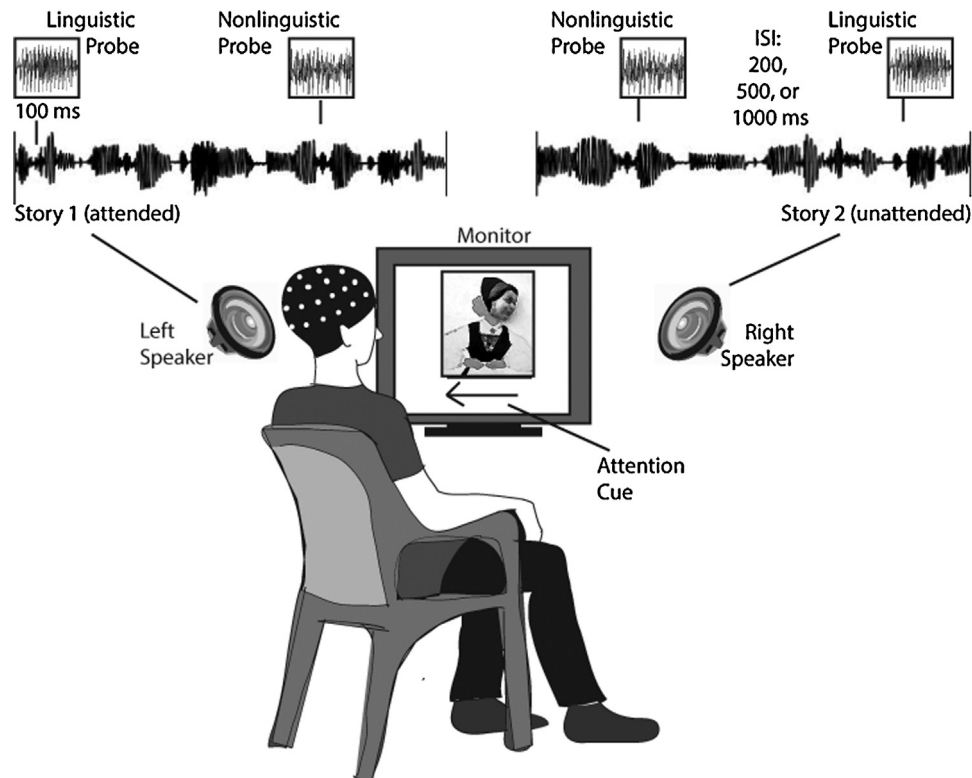


Fig. 1. Diagram of the experimental paradigm and apparatus. Participants were instructed to attend to the story presented from the left or the right loudspeaker while images accompanying the attended story were presented on a computer monitor. ERPs were recorded to probe stimuli superimposed on both the attended and unattended narrative. Probes were 100 ms duration with ISI of 200, 500, or 1000. The waveform excerpts from the stories are not on the same time-scale as the probes.

based on moving window peak-to-peak changes in eye channels across a 200 ms window, moving in 50 ms increments. Individual artifact rejection parameters were selected for each subject on the basis of visual inspection of the raw EEG to identify the smallest amplitude changes associated with eye movements or blinks. Manual artifact rejection was employed after the automatic ERPLAB procedures, to ensure accuracy of artifact marking. Following artifact rejection, epochs were low-pass filtered using a two-way, zero-phase lag Butterworth filter; the filter order was two times the sampling rate divided by the upper frequency edge (40 Hz), rounded down for averaging and measurement, which occurred across presentation side.

ERPs were averaged and analyzed separately for nonlinguistic (/bzz/) and linguistic (/ba/) probe types due to morphological differences in the ERPs elicited by each probe type in older age groups. Two main measures of the ERPs were obtained, peak-latency and amplitude. There are developmental differences in scalp topography due to differential maturation of evoked-potential generators (Ponton et al., 2000) that make it difficult to determine an ideal a priori method for measuring peak-latency in our dataset since separating electrodes into different groups based on scalp

topography could be influenced by age group and probe type. Similarly, as noted by Luck (2005), peak-latency measures are non-linear and the peak-latency measured from a grand average is not likely to be the same as the average of measurements from single-subject waveforms or even the average of the single-trial peak-latencies within a subject.¹ In addition, our study is complex – it consists of five age groups, two probe types, multiple time windows, and 24 scalp channels included in the analysis (namely F3/4, F7/8, FC5/6, FT7/8, C3/4, C5/6, T7/8, CP5/6, P3/4, P7/8, PO3/4, and O1/2). In light of these complexities and since our goal was to determine whether age or attention affected peak-latency, peaks were identified in each subject from the average across their 24 scalp channels as detailed in the following paragraph.

¹ It is important to note that the peaks measured do not necessarily reflect “components” as defined by Luck (2005): “Scalp-recorded neural activity that is generated in a given neuroanatomical module when a specific computational operation is performed”. Peak amplitudes and latencies in a given ERP waveform may reflect the summation of more than a single neuroanatomical module.

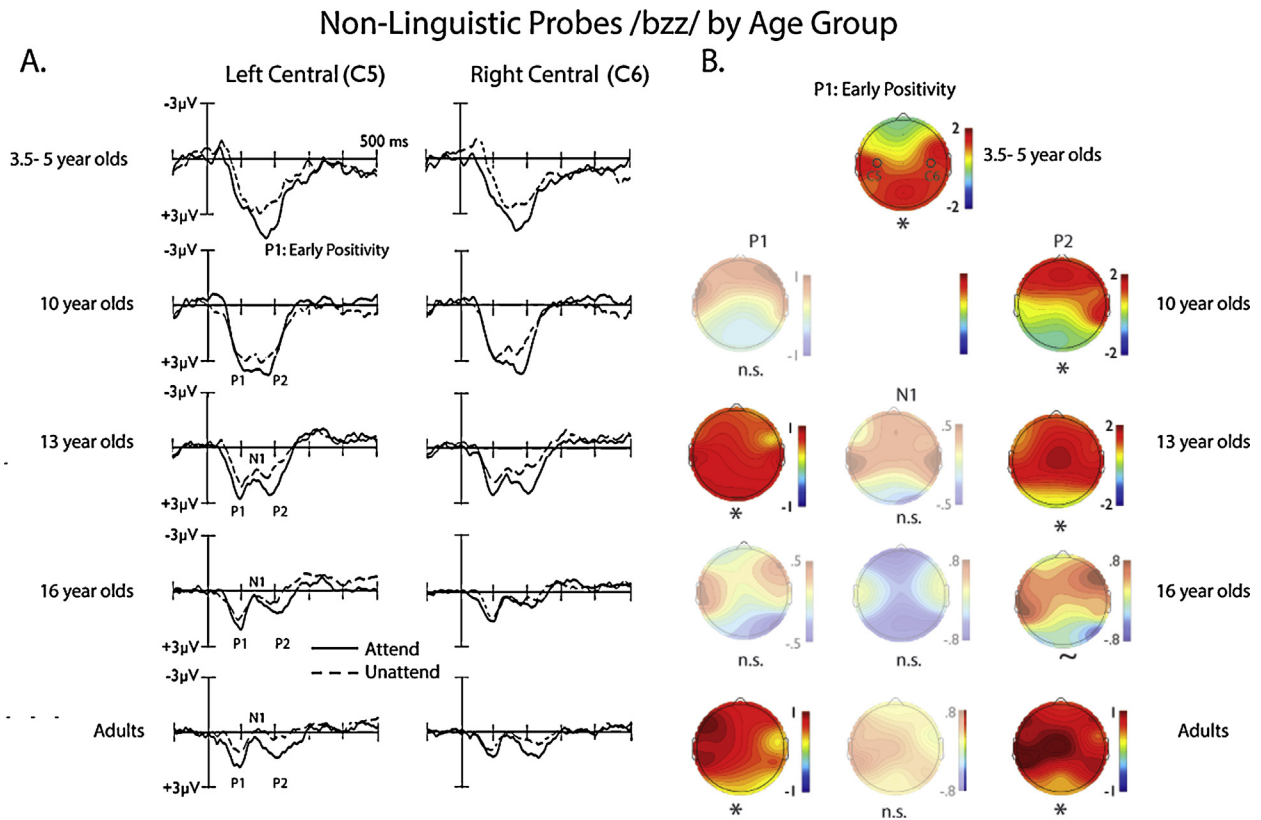


Fig. 2. (A) ERPs elicited by nonlinguistic probes at left and right central electrode sites (C5/6 for illustrative purposes), plotted separately for probes embedded in the attended and unattended narratives. (B) Topographic scalp plots of attention modulations (attend–unattend difference waves) of the primary components of the ERPs for each age group are plotted with individual amplitude scales. Time windows used for each plot can be found in Table 2. Asterisks below the plots indicate a significant difference between attend and unattend amplitudes ($*p < .05$, $\sim p < .10$ with scalp topography at 50% transparency, n.s. $p > .10$, with scalp topography at 75% transparency. Statistical details are in Table 2).

For nonlinguistic probes, peaks were identified at the early positive deflection in 3–5-year-olds, at an early and late positive deflection in 10-year-olds, and from each deflection in the P1/early-N1/P2 complex in 13-year-olds, 16-year-olds, and adults. For linguistic probes, peaks were identified at the first positive deflection for all age groups, and at the subsequent negativity (late-N1) for 10-year-olds, 13-year-olds, 16-year-olds, and adults. The 3–5-year-olds were not included in the nonlinguistic or linguistic P1 or P2 latency analyses because they only had a single positive peak that could not be characterized as either a P1 or a P2. We measured the amplitude as the average within a 20 ms window centered on the mean latency of each measured peak within the grand average for each age group, averaged across presentation side.

2.2.2.3. A priori statistical analysis. We analyzed peak latency separately for each measured peak with an Attention by Age ANOVA, with attention as a repeated measure and age group as a between-subjects factor. We analyzed the effect of attention and age on the amplitude of each measured peak separately for each age group with repeated-measures ANOVAs. Factors of attention (Attended, Unattended) and scalp distribution were included in a 2 (Hemisphere: Left, Right Hemisphere) \times 2 (Laterality: Lateral, Medial site) \times 6 (Anteriority: Frontal, Frontocentral, Central, Central-Parietal, Parietal, Parietal-Occipital) ANOVA. Electrodes included in the final analyses were F3/4, F7/8, FC5/6, FT7/8, C3/4, C5/6, T7/8, CP5/6, P3/4, P7/8, PO3/4, and O1/2. Greenhouse–Geisser corrections were made for factors with more than two levels. Planned contrasts between children and adults were Bonferroni corrected and reported as significant at $\alpha < .05$. For non-adults,

we also report differences at $\alpha < .10$ as trends, since developmental differences may be emerging at small amplitudes or may be variable across individual children and we do not wish to make binary statements about attention effects being present or not-present without noting that some effects may be emerging in younger age groups at lower statistical thresholds. Differences reported at $p < .10$ should not be interpreted as statistically significant.

2.2.2.4. Exploratory analysis across age groups. The main a priori analysis we conducted was to characterize the attention effects on peak amplitude and latency within each age group. As an exploratory analysis we directly compared attention modulation across age groups to determine whether attention effects at certain peaks better distinguished the age groups than others. In general, the amplitudes of ERPs decrease with age, so it was necessary to normalize amplitudes across age groups; we divided the difference between attend and unattend by the mean amplitude of the unattended waveform over the channels in the analysis. This calculation, a ratio of the difference-wave amplitude to the unattended waveform amplitude, yields positive values when both attend and unattend measures are positive or both are negative. The result multiplied by 100 is the percent-increase of attend relative to unattend. Normalization procedures are non-linear and can yield unrealistically large values for noisy data or for data where the denominator is close to zero; values outside 3 SDs from the mean were excluded from the analysis.

Since we were adding the additional factor of age to the analysis we performed a simpler ANOVA (Hemisphere (Right, Left) \times Age Group) excluding the noisier temporal and posterior channels, with

percent change of attended relative to unattended amplitudes as the dependent variable. Note that there are two things that are normalized with this approach: (a) the amplitude of the attended waveform is normalized to unattend and (b) since we are using peaks to center the amplitude measurements for each age group, the analysis is indirectly correcting for the latency within each age group.

2.2.2.5. Follow-up analysis on difference waves. We also tested whether attend minus unattend difference waves indicate that attention operates differently across age groups – an approach that can be useful in determining whether attention changes with age likely reflect gain-control of exogenous ERPs or additional endogenous processes superimposed on the underlying waveforms (Hansen and Hillyard, 1980; Woldorff and Hillyard, 1991; Sanders et al., 2006). A visualization of the shape and topography of the difference waveform is used to infer whether gain control of stimulus evoked (exogenous) potentials is a likely mechanism, although as noted by Woldorff and colleagues (1991) it does not rule out that other mechanisms are also operating perhaps with coincidentally similar morphology and topography.

Starting at 50 ms and ending at 500 ms, we tested whether the difference between attend and unattend was significantly different than zero (two-tailed $p < .05$). We also applied a topographical and temporal constraint; a difference had to span at least 3 time bins (30 ms) and be significant across 4 adjacent electrodes to be reported as significant. Difference-wave scalp topographies were plotted for time ranges that met statistical significance to allow comparison to topographies at identified peaks in the a priori analysis.

3. Results

3.1. Nonlinguistic probes

As shown in Fig. 2, for nonlinguistic probes (/bzz/) there was a shift in the morphology, latency, and amplitude of auditory ERPs and the attention-effect with age. This manifested as an early positivity from approximately 100 to 400 ms in the youngest children and developed into a P1–N1–P2 complex in adolescents and adults.² This shift is consistent with previous reports of auditory evoked potential maturation that indicate that the N1 is clearly differentiated from the broad positivity by 12 years, which previous researchers identified at lateral central electrodes as an N1b (Ponton et al., 2000).

3.1.1. Nonlinguistic P1 latency

As shown in Fig. 2, the peak of the earliest positive deflection was at 175 ms in 3–5-year-olds. Note that the latency of this first positive peak for 3–5-year-olds is similar to the P2 latency in 10-year-olds and it may not be directly comparable to P1 processes in older children and adults. Our analysis reflected this observation; only groups aged 10 and older were included in the age by latency analyses for the P1. P1 latency was shorter in older age groups (Fig. 3: Main effect of Age group: $F(3,71) = 52.4, p < .001$) with average latencies at 114 ms in 10-year-olds, 91 ms in 13-year-olds, 85 ms in 16-year-olds, and 83 ms in adults. Bonferroni-corrected contrasts by Age Group ($N = 3$) indicated that P1 latency in adults was significantly shorter than in 13-year-olds ($p = .018$) and 10-year-olds ($p < .001$), but not than in 16-year-olds ($p > .10$). Unlike P1

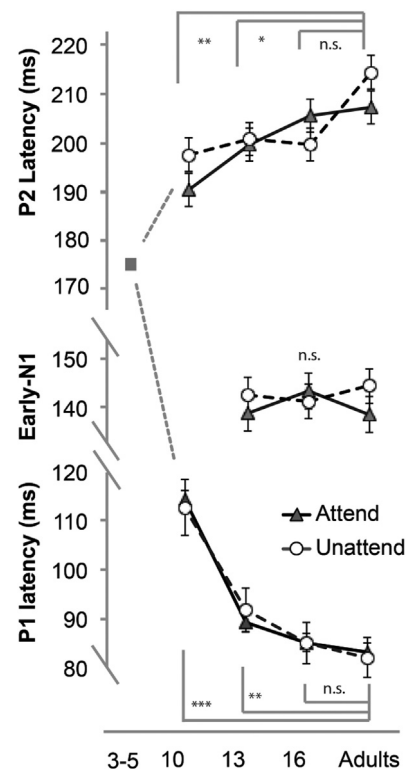


Fig. 3. Peak latencies for the P1 (lower plot), N1 (middle plot), and P2 (upper plot) components evoked by nonlinguistic probes. Latencies are not shown separately for 3–5-year-olds due to their waveform morphology consisting of a single positive-going deflection. Significant differences between the older children and adults are marked by asterisk (*, $p < .05$; **, $p < .01$; ***, $p < .001$, details are in the results section).

amplitude, we did not find evidence that P1 latency was affected by attention ($p > .10$).

3.1.2. Nonlinguistic probe P1 amplitude

As with our previous samples of preschool-age children using earlier versions of this task, for 3–5-year-olds the attention effect (the difference between the amplitude of the ERPs elicited by the probes in the attended versus the unattended stories) was significant and positive at 165–185 ms (detailed statistics are summarized in Table 2, and are depicted in Fig. 2b). The 10-year-olds shared the prolonged positivity observed in the youngest children, however two distinct peaks, a P1 and P2, were measurable perhaps reflecting the emerging early-N1 measurable in 13-year-olds. At the P1 peak of 10-year-olds (114 ms), the P1 was not significantly modulated by attention ($p > .10$). For 13-year-olds, the P1 peak was significantly later than that of adults (8 ms, see previous section), and at this later latency (91 ms), amplitude modulation with attention was significant ($p < .05$). For 16-year-olds, the P1 had an adult-like latency, but there was only a non-significant trend toward attention modulation at the P1 manifesting as a trend interaction with topography ($p < .10$). Thus, the earliest attention modulation at the P1 may be less reliable or not present in late adolescence, while in adults, attention reliably increased the amplitude of the P1 elicited by nonlinguistic probes, particularly over frontal and left hemisphere electrodes ($p < .001$).

3.1.3. Nonlinguistic probe early-N1 latency and amplitude

Fig. 2 illustrates that the early-latency N1 deflection that was characteristic of adults (peaking at ~140 ms) was measurable at 13 years of age, but not for the younger age groups. Fig. 3 shows that unlike the P1 latency, there was no significant effect of age on early-N1 latency ($p > .10$). In addition, attention did not modulate

² The adult pattern is similar to previous reports of tones embedded in dichotic speech streams although there are differences in terms of the relative amplitude of the P1 to N1 (Hink and Hillyard, 1976).

the amplitude or latency of the early-N1 in 13-year-olds, 16-year-olds, or adults ($p > .10$, Table 2, Fig. 3).

3.1.4. Nonlinguistic probe P2 latency

As shown in Fig. 2, a second positive peak (P2) was clearly distinguishable from the P1/early-N1 complex in 13-year-olds, 16-year-olds, and adults. For 10-year-olds, a later positive peak was measurable, though it was still part of a sustained initial positivity. In contrast with the P1 latency which grew shorter with age, Fig. 3 shows that the latency of the P2 grew longer with age from 193 ms in 10-year-olds, to 200 ms in 13-year-olds, 202 ms in 16-year-olds, and 209 ms in adults (Fig. 3; $F(3,71) = 9.6$, $p < .0001$). Bonferroni corrected contrasts between adults and younger age groups ($N=3$) indicated that adults had a significantly later P2 latency than 10-year-olds ($p < .001$) and 13-year-olds ($p = .045$), but not 16-year-olds ($p = .18$). As with the P1 and N1 latency, there was no effect of attention on the latency of the P2.

3.1.5. Nonlinguistic probe P2 amplitude

As shown in Fig. 2, the modulation of amplitude with attention at the P2 peak was significant for 10-year-olds, 13-year-olds, and adults ($p < .05$, detailed statistics are summarized in Table 2). This effect did not reach significance in 16-year-olds ($p < .10$), indicating that attention modulation of P2 amplitude was less reliable or was not present in 16-year-olds.

3.2. Linguistic probes

As shown in Fig. 4, linguistic probes (/ba/) elicited a broad positivity for 3–5-year-olds, a similar morphology to the waveform elicited by nonlinguistic probes. However, in older age groups, the ERP morphology was different from than the morphology elicited by nonlinguistic probes. In 10-year-olds, there was a prominent late, relatively sustained, negativity that was distinct from the early-N1 characteristic of nonlinguistic probes. The later negativity was also present in 13-year-olds, 16-year-olds, and adults. We use the term “late-N1” in our analysis and discussion to refer to this first negative waveform that peaks around 200 ms in adults to distinguish it from the “early-N1” evoked by non-linguistic probes. Further support for the idea that this later negativity is distinct from the early-N1 is shown in Fig. 4, where 13-year-olds and 16-year-olds show a slight deflection in the rising phase of the late-N1 at about 140 ms, the same latency of the early-N1 measured in the analysis of nonlinguistic probes.

3.2.1. Linguistic probe P1 latency

As shown in Figs. 4 and 5, the peak of the earliest positive deflection in 3–5-year-olds was at 171 ms for linguistic probes, and as with non-linguistic probes the average latency of the linguistic probe P1 decreased with age in the older age groups. The latency decreased from 107 ms at 10 years old, to 101 ms at 13 years old, 92 ms at 16 years old, and 86 ms in adults ($F(3,71) = 15.0$, $p < .001$). Bonferroni corrected contrasts by age ($N=3$) indicated that the latency of the P1 in adults was longer than for 10-year-olds and 13-year-olds ($p < .001$; $p < .001$), but not for 16-year-olds ($p > .10$).

Unlike for nonlinguistic probes, attention affected the P1 latency for linguistic probes differently by age group (Age \times Attention interaction: $F(3,71) = 3.67$, $p = .016$). While 10-year-olds had a marginally shorter latency for unattended probes relative to attended (9 ms), 13-year-olds, 16-year-olds, and adults had a marginally longer latency for unattended probes relative to attended (–7 ms, –2 ms, and –3 ms, respectively). This effect is also apparent in Fig. 4, where the increased amplitude of the attended P1 leads to a slightly later peak in 10-year-olds.

Table 2
Detailed statistical results for the analysis of nonlinguistic probe amplitude. We analyzed the effect of attention and age on the amplitude of each measured peak separately for each age group with repeated-measures ANOVAs. Factors of attention (Attended, Unattended) and scalp distribution were included in a 2 (Hemisphere: Left, Right Hemisphere) \times 2 (Laterality: Lateral, Medial site) \times 6 (Anteriority: Frontal, Frontocentral, Central, Central-Parietal, Parietal, Parietal-Occipital) ANOVA.

Component	Age	Latency	Summary	Attention	Att \times hemi	Att \times ant	Att \times lat	Att \times hemi \times lat	Att \times ant \times lat	Att \times ant \times hemi \times lat	
Early positivity	3–5 yo	(165–185)	**	$F(1,19) = 4.5$ $p = .046$	$F(1,19) = 5.2$ $p = .035$		$F(1,19) = 12$ $p = .003$	$F(2.8,53) = 2.7$ $p = .055$	$F(1,19) = 4.3$ $p = .051$	$F(3,71) = 4.0$ $p = .01$	$F(3,63) = 3.8$ $p = .012$
	10 yo	(104–124)	n.s.				$F(1,17) = 7.3$ $p = .015$			$F(3,1,52) = 2.3$ $p = .09$	
P1	13 yo	(81–101)	*	$F(1,17) = 8.1$ $p = .011$							
	16 yo Adults	(76–96) (73–93)	n.s. ***	$F(1,19) = 21$ $p < .001$	$F(1,19) = 3.9$ $p = .062$		$F(1,19) = 27$ $p < .001$			$F(3,6,67) = 3.8$ $p = .01$	
Early-N1	13 yo	(131–151)	n.s.								
	16 yo Adults	(132–152) (131–151)	n.s. n.s.								
P2	10 yo	(184–204)	*		$F(1,18) = 5.9$ $p = .025$		$F(1,18) = 3.6$ $p = .075$			$F(3,5,63) = 2.3$ $p = .080$	
	13 yo	(190–210)	***	$F(1,17) = 16$ $p = .001$			$F(1,17) = 16$ $p = .001$				$F(3,0,50) = 2.4$
	16 yo	(193–213)	~		$F(1.5,25) = 2.9$ $p = .090$						
	Adults	(200–220)	**	$F(1,19) = 8.8$ $p = .008$			$F(1,19) = 8.2$ $p = .01$			$F(1,19) = 3.3$ $p = .084$	

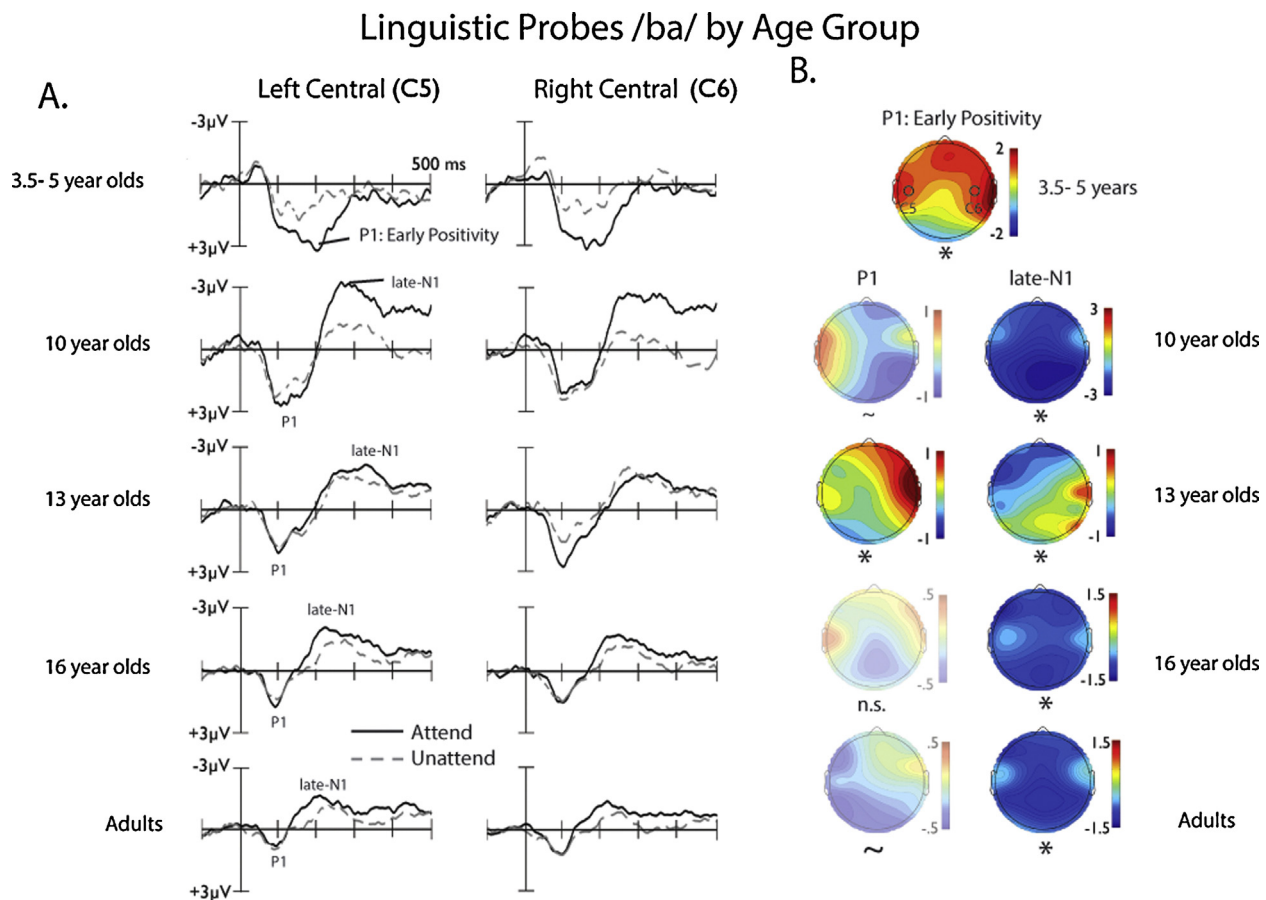


Fig. 4. (A) ERPs elicited by linguistic probes at left and right central electrode sites (C5/6 for illustrative purposes), plotted separately for probes embedded in the attended and unattended narratives. (B) Topographic scalp plots of attentional modulations (attend–unattend difference waves) of the primary components of the ERPs for each age group are plotted with individual amplitude scales. Time windows used for each plot can be found in Table 3. Asterisks below the plots indicate a significant difference between attend and unattend amplitudes ($*p < .05$, $\sim p < .10$ with scalp topographies at 50% transparency, n.s. $p > .10$, with scalp topographies at 50% transparency. Statistical details are in Table 3).

3.2.2. Linguistic probe P1 amplitude

As with the nonlinguistic probes, the 3–5-year-olds showed the typical early positivity from 100 to 300 ms for linguistic probes, which peaked around 171 ms and was modulated by attention ($p < .05$, Table 3). The 10-year-olds did not show significant P1 amplitude modulation with attention at the peak (108 ms), but trend-level effects ($p < .10$, Table 3) may indicate that an attention effect at the P1 was emerging in this age group ($p < .10$). The P1 in 13-year-olds, peaking at 102 ms, was modulated by attention, manifesting as a right-lateralized positive attention effect (Fig. 4B, $p < .001$), and a trend toward a larger modulation over central anterior sites ($p < .10$). For 16-year-olds, attention did not modulate the P1 amplitude at 92 ms ($p > .10$) and was not significant in adults (attention by hemisphere interaction at 90 ms, $p = .10$). Detailed statistics are summarized in Table 3.

3.2.3. Linguistic probe late N1 latency

In 3–5-year-olds, there was no late-N1 present. By 10 years of age, the late-N1 was prominent. The peak latency of the late-N1 decreased with age from 251 ms in 10-year-olds, 262 ms in 13-year-olds, 243 ms in 16-year-olds, and 208 ms in adults ($F(3,71) = 50.4$, $p < .001$). Bonferroni corrected contrasts ($N = 3$) indicated that 10-year-olds, 13-year-olds, and 16-year-olds had longer late-N1 latencies than adults (all $p < .001$). This finding for the late-N1 is in contrast to the latency measures of the early-N1 for nonlinguistic probes, which showed no latency change with age.

As with the linguistic P1, the effects of attention on latency of the linguistic late-N1 interacted with age in the 10-year-olds, who had a longer latency for attended than unattended probes ($F(3,71) = 4.2$, $p < .01$), but not for the older age groups.

3.2.4. Late-N1 amplitude

In 3–5-year-olds, there was no late-N1 present. By age 10 years, attention robustly increased the late-N1 amplitude ($p < .001$). At age 13 years, attention interacted with hemisphere (Attention \times Hemisphere: $F(1,17) = 14.8$, $p = .001$). By age 16 years, attention increased the late-N1 amplitude ($p < .05$), as it did with adults ($p < .05$). Detailed statistics are summarized in Table 3.

3.2.5. Analyses across age groups

In an exploratory analysis we expressed the attention modulation as the ratio of the difference between attend and unattend relative to the amplitude of the unattend waveform, normalizing amplitude by age in order to perform statistical comparisons across ages. The only significant effect of age on the normalized amplitude of the difference wave was for the nonlinguistic P1 where adults show a larger P1 percent change over the left than the right relative to other age groups (Age \times Hemi Interaction: $F(3,70) = 4.0$, $p = .01$, Fig. 6) indicating that with this analysis approach, the early-latency attention effects may best distinguish the age groups.

Table 3
Detailed statistical results for the analysis of linguistic probe amplitude. We analyzed the effect of attention and age on the amplitude of each measured peak separately for each age group with repeated-measures ANOVAs. Factors of attention (Attended, Unattended) and scalp distribution were included in a 2 (Hemisphere: Left, Right Hemisphere) × 2 (Laterality: Lateral, Medial site) × 6 (Anteriority: Frontal, Frontocentral, Central, Central-Parietal, Parietal, Parietal-Occipital) ANOVA.

	Age (years)	Latency (ms)	Summary	Attention	Att × hemi	Att × ant	Att × lat	Att × hemi × ant	Att × ant × lat	Att × ant × hemi × lat
Linguistic	3–5	(161–181)	***	$F(1,19)=3.1$ $p=.096$	$F(1,19)=2.9$ $p=.10$	$F(1.6,29)=5.3$ $p=.016$	$F(1,19)=3.7$ $p<.001$	$F(2.6,49)=4.2$ $p=.014$	$F(1,19)=6.2$ $p=.022$	$F(4.1,78)=5.2$ $p=.001$
	10	(98–118)	~		$F(1,18)=3.6$ $p=.073$			$F(2.8,50)=2.3$ $p=.096$	$F(1,18)=4.4$ $p=.051$	
	13	(92–112)	***		$F(1,17)=16$ $p=.001$	$F(1.7,29)=3.4$ $p=.053$				
P1	16	(82–102) (76–96)	n.s.		$F(1,19)=3.4$ $p=.083$					
	Adults		~		$F(1,17)=14.8$ $p=.001$					
Late-N1	10	(241–261)	***	$F(1,18)=16.5$ $p=.001$			$F(1,18)=15$ $p=.001$		$F(1,18)=3.8$ $p=.067$	$F(2.9,51)=3.8$ $p=.02$
	13	(252–272)	***						$F(1,17)=3.7$ $p=.072$	
	16	(233–253)	*	$F(1,17)=5.6$ $p=.031$		$F(1,17)=4.8$ $p=.042$			$F(1,17)=3.8$ $p=.067$	$F(3.4,58)=2.1$ $p=.10$
Adults	(198–218)	***	$F(1,19)=35$ $p<.001$		$F(2.3,44)=3.2$ $p=.044$		$F(1,19)=20$ $p<.001$		$F(3.9,74)=5.8$ $p<.001$	

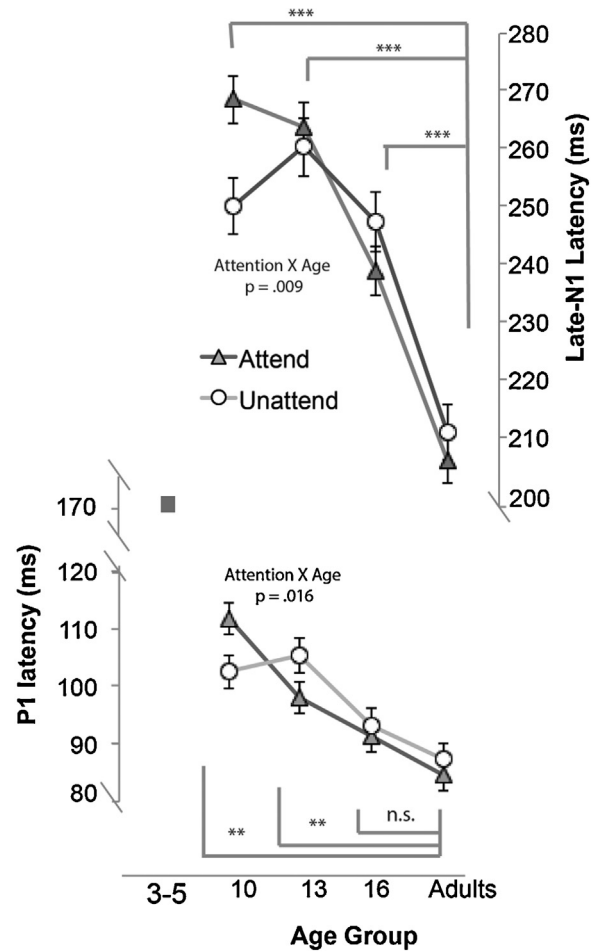


Fig. 5. Peak latencies for ERPs evoked by linguistic probes at the P1 (lower plot) and late-N1 (upper plot) components. Latencies are shown separately for 3–5-year-olds due to their waveform morphology consisting of a single positive-going deflection. Significant differences between children ages 10 and older and adults are marked by asterisk (* $p < .05$; ** $p < .01$, details are in Table 3).

3.2.6. Difference wave analyses

As an additional follow-up analysis to better understand when and whether the attention effects are consistent with a gain control mechanism and whether the a priori approach adequately characterized the attention effect, the difference between attend and unattend was compared to zero using a running t-test as described in the methods; Table 4 summarizes the results with Fig. 7 illustrating the topography for time periods which met the criteria for statistical significance.

3.2.6.1. Nonlinguistic probes. Overall, Fig. 7 demonstrates that difference waves had a multiphasic morphology that was similar to the attend and unattend waveforms for each age group and the significant time periods in the time-bin analysis of the difference wave corresponded with the P1-N1-P2 peak-latencies that were measured in the a priori analysis. This can be considered evidence for gain-control modulation (Woldorff and Hillyard, 1991). Two exceptions to this generalization occurred but should be interpreted with caution in this exploratory context unless subsequently replicated: First, a positive attention effect for the 3–5-year-olds was significant from 50 to 100 ms. Second, attention modulation later than 250 ms was significant in two age groups (ages 10 and 16 years).

3.2.6.2. Linguistic probes. As with the a priori peak analysis of the P1, the difference wave analysis indicated that attention

Amplitude of difference wave compared across ages, normalized by unattend amplitude

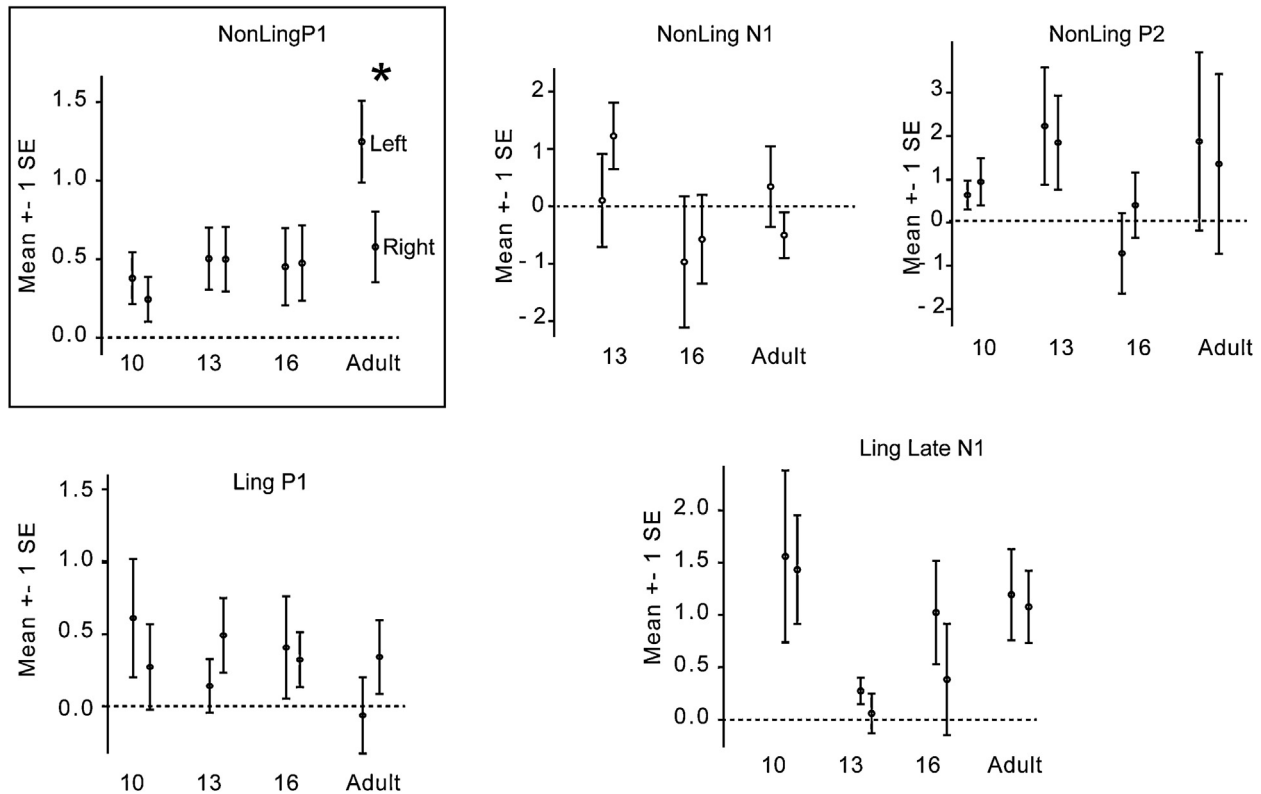


Fig. 6. Normalized amplitude increase for attended probes relative to unattended probes across age groups. Note that this analysis, by measuring peak amplitudes, does not take latency differences between age groups, such as the decreasing latency of the P1 with age, into account. Bars represent the average amplitude increase over left versus right hemispheres (error bars represent 1 SE). The only significant effect of age on amplitude of attend relative to unattend was for the nonlinguistic P1 where adults show a larger P1 percent change over the left than the right relative to other age groups.

modulation at the earliest P1 latency was only significant for 13-year-olds, and the peak of their difference wave aligned with the measured P1 peak in accord with a potential gain-control account of attention modulation. At the peak of the early positivity in 3–5-year-olds, the peak attention modulation was later than the measured peak latency of 171 ms providing mixed evidence for gain control.

As shown in Fig. 7, for the late-N1, there was not strong concordance between the latency of measured peaks in the a priori analysis and peaks in the difference wave. It may be that a peak-based approach is less appropriate for the late-N1 since it is more sustained and indeed was analyzed as a broad time range in a previous study (Sanders et al., 2006). However, both the peak-based and time-bin approaches yielded significant differences in this later time range with scalp topographies of significant attention effects that were similar across age groups.

4. Discussion

4.1. Summary

The ability to selectively allocate attention changes with development (Geffen and Sexton, 1978; Hiscock and Kinsbourne, 1980; Takio et al., 2009), is different in special clinical populations (Knight et al., 1981), and can be enhanced in early-childhood with training (Neville et al., 2013; Stevens et al., 2013, 2008) but, the transition from the early positivity characteristic of young children to that of older adolescents and adults – particularly in noisy environments with competing speech stimuli – has not been fully characterized (Lackner et al., 2013). Using an ecologically valid dichotic listening task, we measured ERPs to linguistic and nonlinguistic auditory probes embedded in simultaneously presented attended and unattended stories. We documented robust maturational changes in

Table 4

Difference wave analysis. The difference between attend and unattend was compared to zero using a running *t*-test as described in the methods. A “+” indicates a positive voltage difference while a “–” indicates a negative voltage difference. See Fig. 7 for the scalp topography for time periods which met the criteria for statistical significance.

	Age (years)	Early <100 ms	Middle 100–250 ms	Late 250–500 ms
NonLing	3–5	50–100 (+)	160–200 (+)	None
	10		160–200 (+)	250–500 (–)
	13	50–90 (+)	180–220 (+)	None
	16		210–240 (+)	320–360 (+)
	Adults	70–100 (+)	160–240 (+)	None
Ling	3–5	120–260 (+)		270–310 (+) 350–500 (+)
	10			220–500 (–)
	13	60–120 (+)	190–230 (–)	310–470 (–)
	16		110–250 (–)	280–460 (–)
	Adults		120–230 (–)	280–450 (–)

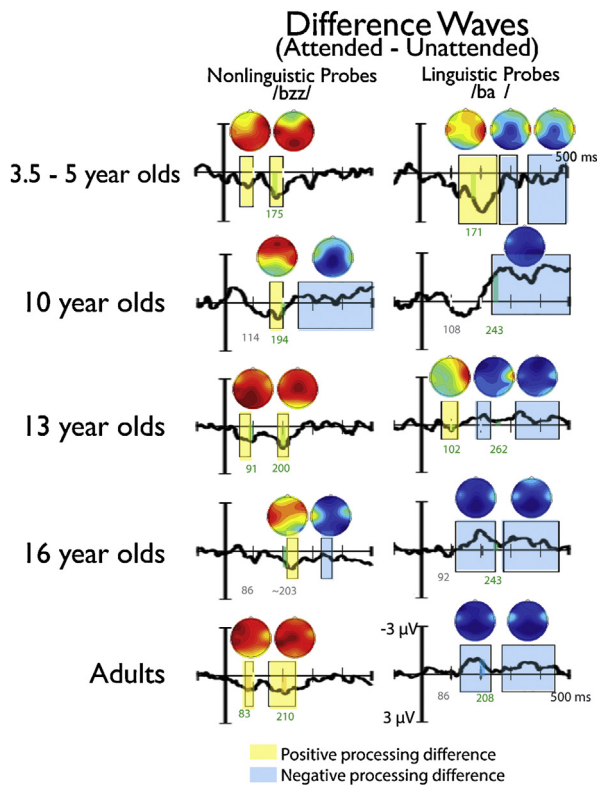


Fig. 7. Average difference waves and scalp topographies for attended minus unattended ERP waveforms by age group for nonlinguistic and linguistic probes. Rectangles overlaid on the ERP indicate time-periods that met the criteria for statistical significance in a running *t*-test analysis of 10 ms time-bins (see Section 2). Yellow rectangles highlight positive deflections and blue rectangles highlight negative deflections in the difference wave. Scalp topographies are plotted for significant time-bins above the difference wave. To facilitate comparison to the previous analyses, we indicated the peak latency identified in the a priori peak-measurement analysis of the auditory ERPs as colored numbers below each plot. Green numbers indicate a statistically significant modulation in the a priori peak-amplitude analysis and gray numbers indicate peak amplitude differences that did not reach statistical significance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

auditory evoked potentials that differed by probe type demonstrating that attention interacts with maturing ERP morphology and latency across early childhood through young adulthood.

4.2. Maturation of auditory ERPs

To determine how auditory attention develops, it is important to first consider the maturation of auditory evoked potentials. Previous research has shown that auditory ERPs undergo considerable maturation throughout childhood and adolescence, including changes to amplitude, morphology, and latency (Lamm et al., 2006; Ponton et al., 2000, 2002; Ridderinkhof and van der Stelt, 2000; Rueda et al., 2004; Segalowitz et al., 2010; Tonnquist-Uhlen et al., 2003). Morphological changes with maturation in our study are striking; for example, in early childhood, auditory ERPs consist of a broad positivity from 100 to 300 ms, while the P1–N1 complex that is characteristic of adults does not emerge until early adolescence. The reasons for these changes in amplitude, latency, and morphology are complex and reflect synaptic changes such as proliferation and pruning, physical changes to anatomy affecting the orientation of dipoles, changes to maturing neurotransmitter systems, and increased myelination affecting speed of processing and frequencies of ongoing oscillations (for a review see Segalowitz et al., 2010) or changes in cortical response variability (Strait et al., 2014). Considering these complexities in interpretation, tracking

the developmental trajectory of maturing auditory potentials is necessary for determining whether they are modulated by auditory attention at different stages of development.

4.2.1. Maturation of speech and non-speech processing

One contribution of the present study is clarification of the results at the N1 latency for linguistic and non-linguistic probes identified in previous studies (Coch et al., 2005; Sanders et al., 2006). In the present study, comparison of the waveforms for 10-year-olds, who still show an immature sustained positivity in the 100–250 ms latency range, to the waveforms of 13-year-olds, who have a more mature morphology, reveals that the early-N1 is likely to be the emerging component responsible for the striking morphological difference between auditory ERPs in childhood and adulthood. Moreover the early-N1, which has a transient peak that does not vary in latency across age, appears to reflect a different process than the linguistic late-N1, which has a sustained profile with a peak latency that decreases with increasing age. Indeed, a small deflection at around 140 ms (the observed peak latency of the nonlinguistic early-N1 in the present study) is visible in the linguistic waveforms for older children and adolescents and may represent the emerging early-N1, which is obscured by the subsequent overlapping sustained late-N1. The late-N1 may indicate that older children and adults have acquired the developmental ability to process linguistic and nonlinguistic probes differently within a narrative context. We think a reasonable speculation is that the late-N1 reflects a sustained, potentially endogenous, processing of the linguistic probes related to their acoustic similarity to the background speech stream; the resolution of this processing could be less efficient, and consequently more sustained, in children.

Overall there appeared to be different developmental trajectories for the two probe types for early versus later components. For both the linguistic and nonlinguistic probes, the peak latency of the early P1 decreased with age, consistent with an explanation that low level auditory processing is speeded as the auditory system matures. For the nonlinguistic probes, the peak latency of the early-N1, which emerged by age 13, did not change with age. The peak latency of the nonlinguistic P2, which has been associated with automatic orienting to novel non-target stimuli, and stimulus classification (see review by Crowley and Colrain, 2004), increased with age. These differences reiterate that developmental changes are not uniform but depend on the acoustic properties of probes and the context in which they are embedded. A further complication is that peaks do not necessarily represent single components, and increased or decreased latency at a given peak could also represent a summation with other components (Luck 2005) that are also changing with development. Other studies have shown that different aspects of the N1 mature differently (Ponton et al., 2002; Tonnquist-Uhlen et al., 2003; Pang and Taylor, 2000) and it is also important to note that various stimuli characteristics and task demands may yield differing results and interpretations for the maturation profile of N1 (Ruhnau et al., 2011; Sussman and Steinschneider, 2009). Our study confirms that it is important to use various types of sounds in developmental studies since auditory evoked potentials showed different maturational profiles for different probe types. Future studies that include a broader variety of probe types, such as environmental sounds (i.e. Sanders and Zobel, 2012), different phonemes, or words as probes, could elucidate the parameters that affect the morphology of auditory ERPs and how they develop.

4.3. Attention effects on auditory ERPs

4.3.1. Adult attention effects at the P1

A motivation for conducting the present study was to better understand whether attention operates as a gain-control

mechanism at early latencies. The evidence in the present study is mixed and seems to depend on probe type. Although both the linguistic and nonlinguistic probes evoked similar P1 components, a P1 significant attention effect at the adult-like peak-latency of 80 ms was observed only for the nonlinguistic probes. This relatively early attentional modulation has been interpreted as a sensory gain control of the auditory input (Woldorff et al., 1987), but has not been consistently reported in selective auditory attention studies. The limited number of studies that have reported a similar early attention effect mainly employed trains of tones with large number of trials (Ahveninen et al., 2003; Woldorff et al., 1987; Woldorff and Hillyard, 1991). This early modulation in the form of a larger P1 has not been reported as significant in studies that employ speech streams (Coch et al., 2005; Hink and Hillyard, 1976; Sanders et al., 2006; Woods, 1990), but individual differences in early modulation of the P1 may account for this (Giuliano et al., 2014). Woldorff and colleagues (1987) attributed the observation of this early effect to task properties including wide channel separation, substantial processing load, and high task difficulty, as well as large numbers of stimuli. Even though we were able to demonstrate this early modulation with considerably fewer trials, the general characteristics of the task might have helped to elicit an early attention effect. In our paradigm, the two channels were widely separated by both ear of entry and by story content. Moreover, the dense auditory environment created a substantial processing load. In addition, not the difficulty of the task, but the relative ease of following speech passages, might have directed the participants to attend more closely to the designated channel.

Although task properties might be crucial in understanding why this early attention effect was observed in our paradigm, they remain insufficient in explaining why only the nonlinguistic probes elicited the P1 attention effect in adults, and future studies will need to address this potential discrepancy. For example, when altering the balance of probes such that linguistic probes occurred more frequently than nonlinguistic probes (66% and 33%, respectively), the P1 attention effect was only observed for linguistic probes and importantly, the magnitude of the P1 attention effect relates to individual differences in working memory capacity, such that individuals with greater capacity show a larger P1 attention effect (Giuliano et al., 2014). These results suggest that the early P1 is sensitive to top-down attention control signals in a manner that is sensitive to individual differences, and that this effect may be observed for linguistic and nonlinguistic probe types. In the present study, the exploratory normalization analysis emphasized that hemispheric differences in P1 modulation may be an important feature of adult-like early modulation of auditory processing. It would be informative to examine whether early P1 attention-modulation was reliable in the same individuals across different testing sessions with diverse probe-types, or whether early attention-modulation reflected more transient aspects of their attention state, such as within-session attentiveness.

4.3.2. Attention effects on the P1 across development

Because peak latencies of the P1 decreases with age, the first question is whether or not younger children show attention modulation at the P1 latency that is typical for their age. In our initial peak-based analysis 13-year-olds and adults had significant attention modulation of their P1, though in 13-year-olds this is nearly 10 ms later than the adults, yet this did not reach significance for 16-year-olds. For linguistic probes, early modulation at the P1 latency was weak or absent for all but 13-year-olds. In our follow-up analysis for which amplitudes and peak-latencies were normalized across age groups, it appears that some attention increase was present at the nonlinguistic P1 for all age groups, but with a stronger left-hemispheric difference for adults. This suggests that the attentional modulation of P1 continues to mature in

late adolescence and an important question to address in future studies is whether there are hemispheric differences in the development of auditory attention. Regardless, these results seem to implicate the presence of a complex developmental trajectory for selective auditory attention across adolescence, which has been reported in other domains of cognitive function and brain development (Blakemore and Robbins, 2012; Dumontheil et al., 2010).

This pattern of results is intricate, but auditory attention development might not be linear across development. While the auditory system is maturing, the neural substrates supporting attention modulation of early sensory processing, such as frontal and parietal cortices are also maturing (Bava et al., 2010; Carper et al., 2002; Casey et al., 2008; Gogtay et al., 2004; Knight et al., 1989; Lenroot and Giedd, 2006; Mabbott et al., 2006; Shaw et al., 2008; Groeschel et al., 2010; Shaw et al., 2006; Sowell, 2004). This maturation includes increased myelination that could affect the speed of processing, as well as the speed and stage of processing at which top-down modulation can exert its influence. In light of these complexities, research should be cautious in combining samples of children and adolescents across age groups that span different phases of auditory and attention development.

This observation also highlights the methodological importance of accounting for maturational changes in underlying waveforms when analyzing attention effects. For example, using the same time windows across age groups with different peak latencies (as in Berman and Friedman, 1995) may obscure earlier-latency attention effects in younger children. For example, for the nonlinguistic and linguistic probes, the auditory evoked potentials for 3–5-year-olds showed a broad positivity with attention modulating the earliest positive peak. However, this initial peak was closer in latency to the P2 observed in the older age groups. The 10-year-olds had a sustained early positivity similar to that of the 3–5-year-olds in our study, as well as that of 3–8 year-olds reported in previous studies (Coch et al., 2005; Sanders et al., 2006), but an earlier P1 was measurable in 10-year-olds. Without accounting for latency shifts across development it would not be clear that attention is operating distinctly on different components of the auditory evoked-potentials.

4.3.3. Later attention effects across development

As with adults, evidence for a gain-control view of attention modulation in children and adolescents is mixed and seems to depend on probe type. Evidence in favor of the gain-control view of attention modulation comes from the exploratory difference wave analysis that demonstrates a multiphasic morphology of attention modulation for all age groups with peaks and topographies in harmony with the measured peaks in the evoked potentials in the P1–N1 and P2 latency range. However, a pure gain-control account of attention modulation for non-overlapping components would predict N1 attention modulation similar to that reported by Woldorff and colleagues (1991) while in our acoustically crowded paradigm it appears that the positive modulation of the P1 may have extended into the early N1 latency, perhaps masking amplitude modulation at the N1. An alternative account that must be considered is that additional endogenous components are generated in the N1 latency range perhaps with a similar scalp distribution (Hansen and Hillyard, 1980). The attention effects detected with the difference wave time-bin analyses revealed prolonged attention effects in the 300–500 ms time range during this later time window that were sustained beyond the late-N1 peak. Sustained attention effects for the linguistic probes were also reported for 6–8 year-olds and adults in a previous study (Sanders et al., 2006) and may indicate additional endogenous processing of the probes. These sustained attention effects for the linguistic probes were evident across all age groups.

The late-N1 amplitude in 10-year-olds was clearly modulated by attention, occurred later than that of adults, and its latency also increased with attention. This pattern suggests that the late-N1 likely reflects ongoing processing of the linguistic probes, with larger amplitudes when the probes appear in the attended story. It is interesting to note that the probes, while appearing in the same spatial location as the attended story, are not relevant to performing the task (i.e. listening to the story and answering questions at the end) and so a shorter adult-like duration of this sustained processing with age may indicate increased efficiency.

4.3.4. Caveats to cross-sectional approaches

As with any developmental research, we urge caution in very strict interpretations of when in development attention modulation of early auditory processing may come online since individual differences in development are striking. For example, in a recent report with a sample of 48 adolescents 12–14 years of age, a larger “early frontal positivity” near 100 ms to to-be-ignored tones was associated with poorer executive functions, highlighting the importance of individual differences³ (Lackner et al., 2013). Approaches that average across a sample by age, such as ours, have the disadvantage of overlooking individual differences in maturation and in cognitive development. In addition, the current sample of adolescents with high maternal education might not be representative of typical adolescents from more varied socioeconomic status backgrounds, an empirical question that we continue to address in our research (Neville et al., 2013). Nonetheless, the broad strokes we use in the present study are necessary to establish a framework for understanding how attention typically develops in children and adolescents before more detailed characterization of individual differences at different ages can take place.

4.4. Cognitive development

Late childhood through adolescence is a dynamic period of development during which profound changes are observed in brain structures (Lebel and Beaulieu, 2011; Houston et al., 2013). Consequently, ongoing development of performance through adolescence has been documented in various other aspects of cognition (Kail, 1991), reasoning (Huizenga et al., 2007), decision-making (Crone and van der Molen, 2004), inhibitory control (Luna et al., 2013), creative thinking (Kleibecker et al., 2013), and risk-taking (Crone et al., 2008). Similar developmental changes throughout adolescence have also been reported for verbal and visuospatial working memory span tasks (Gathercole et al., 2004; Kwon et al., 2002; Luciana et al., 2005; Luna et al., 2004). These developmental changes may be associated with, or partially driven by, the maturational changes we observed in selective attention in this study. Our study offers insight into how selective attention in the context of a crowded listening environment matures into adulthood, while considering several factors such as how attention might interact with different features of auditory distractors and how this process itself might interact with age. Gaining a better grasp of how

auditory selective attention matures into adulthood can further our understanding of cognitive skills, particularly those that are often trained in a crowded classroom environment, as well as how deficits and disorders in these domains emerge or persist from early childhood into adulthood.

5. Conclusion

In conclusion, we used an ecologically valid speech-based dichotic listening task that is engaging to participants ages 3 through adulthood to investigate how auditory attention develops into adolescence in an acoustically noisy environment. The latency at which attentional processes operate continues developing into adolescence and interacts with the morphology of maturing auditory event related potentials. We further demonstrated the importance of considering more than one probe type when tracking the development of auditory processing and attention modulation. While at the earliest latencies, there is evidence for gain-control modulation of maturing auditory evoked potentials for nonlinguistic probes, for linguistic probes evidence is mixed with sustained attentional modulation, indicating additional, potentially endogenous processing at later latencies. While our study provides a comprehensive depiction of the typical developmental trajectory of selective auditory attention, further research is warranted to understand the factors that account for vulnerabilities of such neural mechanisms from early childhood into adulthood.

Conflict of interest

None declared.

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³ Lackner and colleagues (2013) suggest that the early frontal positivity in adolescents and adults that is elicited by pure tones in a dichotic listening task may be a different component than a classical P1 component because it is not consistently modulated by attention allocation and because the P1/P50 typically requires high-pass filtering and a large number of trials to be observed, and they suggest that their EFP has a frontal generator rather than generators in the auditory cortex. In this report and others (Giuliano et al., 2014), we have used the P1 terminology used by Ponton and colleagues (Ponton et al., 2000, 2002) as well as Hillyard and colleagues (e.g. Hink and Hillyard, 1976), and note that bilateral generators in the superior temporal plane also lead to frontally distributed scalp topographies. However, we acknowledge that there is not yet enough evidence to exclude the possibility that this very early positivity reflects a different component with different generators.

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