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Neuropsychologia 44 (2006) 2126–2138

NEUROPSYCHOLOGIA

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Selective auditory attention in 3- to 5-year-old children: An event-related potential study

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Received 8 July 2005; received in revised form 24 September 2005; accepted 12 October 2005
Available online 10 November 2005

Abstract

Behavioral and electrophysiological evidence suggests that the development of selective attention extends over the first two decades of life. However, much of this research may underestimate the attention abilities of young children. By providing strong, redundant attention cues, we show that sustained endogenous selective attention has similar effects on ERP indices of auditory processing in adults and children as young as 3 years old. All participants were cued to selectively attend to one of two simultaneously presented stories that differed in location (left/right), voice (male/female), and content. The morphology of the ERP waveforms elicited by probes embedded in the stories was very different for adults, who showed a typical positive-negative-positive pattern in the 300 ms after probe onset, and children, who showed a single broad positivity during this epoch. However, for 3- to 5-year-olds, 6- to 8-year-olds, and adults, probes in the attended story elicited larger amplitude ERPs beginning around 100 ms after probe onset. This attentional modulation of exogenously driven components was longer in duration for the youngest children. In addition, attended linguistic probes elicited a larger negativity 300–500 ms for all groups, indicative of additional attentional processing. These data show that with adequate cues, even children as young as 3 years old can selectively attend to one auditory stream while ignoring another and that doing so alters auditory sensory processing at an early stage. Furthermore, they suggest that the neural mechanisms by which selective attention affects auditory processing are remarkably adult-like by this age.

Keywords: Development; ERP; N100; Nd; Endogenous attention; N1

1. Introduction

By labeling selective auditory attention "the cocktail party effect," Cherry (1953) might have implied that it is something in which only adults fully engage. Indeed, evidence gathered over the past 50 years has indicated that the ability to differentially process relevant and irrelevant information is not fully adult-like until at least the teenage years (e.g., Hiscock & Kinsbourne, 1980; Pearson & Lane, 1991). However, young children certainly have some ability to selectively attend (McKay, Halperin, Schwartz, & Sharma, 1994; Pritchard & Neumann, 2004; Rueda et al., 2004), and attention may play a role in the development of other cognitive skills. Designing tasks to accurately measure selective attention in young children renders it possible to gain a better understanding of how attention mechanisms are established during development and how the maturity of attention systems correlates with the growth of other cognitive and perceptual abilities.

Evidence from behavioral studies of visual and auditory selective attention using traditional tasks suggests that adult-like attentional control is not fully developed until at least after puberty. In dichotic listening tasks, the abilities to correctly recall and recognize information presented to the attended ear while avoiding intrusions from the unattended ear continue to develop beyond the age of 12 years (Asbjørnsen & Bryden, 1998; Doyle, 1973; Hiscock & Kinsbourne, 1980; Pearson & Lane, 1991). In the visual modality as well, the ability to attend to specific features within stimuli, as measured by slowed reaction times for detecting targets when irrelevant features vary, continues to develop until at least the age of 10 years (Shepp, Barrett, & Kolbet, 1987). Finally, in a cross-modal Stroop task, 11-year-olds are worse than adults at suppressing auditorally presented

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0028-3932/$ – see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.neuropsychologia.2005.10.007

color names when asked to identify the color of a visually presented rectangle (Hanauer & Brooks, 2003). Thus, from studies employing classic adult attention tasks across modalities, there is evidence for a prolonged period of development for selective attention systems.

Studies that have more directly manipulated the degree of executive control necessary to complete a task suggest that adult-like control of selective attention can be accomplished at an earlier age under conditions in which external cues direct attention more strongly (Klenberg, Korkman, & Lahti-Nuuttila, 2001; McKay et al., 1994; Shepp & Barrett, 1991; Zukier & Hagen, 1978). For example, in a visual target detection task with various set sizes, 9- and 10-year-old children were able to ignore distractors at peripheral locations to a similar extent as adults only if the complexity of the foveally presented set demanded more attention (Huang-Pollock, Carr, & Nigg, 2002). Studies such as this suggest that with adequate external cues young children can overcome difficulty with sustaining attention over an extended period of time and switching among competing tasks. Overall, the ability to ignore irrelevant information across a variety of more child-directed tasks appears fully developed by the age of 11 (see Lane & Pearson, 1982 for a review).

Studies designed specifically for young children have shown that children can demonstrate adult-like competence in some aspects of attention at even earlier ages. For example, adapting a traditional Posner visual cuing paradigm to be more interesting and child-friendly by employing fish on colorful backgrounds yielded the finding that attention orienting is fully developed before the age of 6 years (Rueda et al., 2004). When attention is indexed by a more implicit measure such as negative priming (unattended items are more difficult to process on subsequent trials) rather than by a more explicit measure such as reaction time, children as young as 5 years old have been shown to perform similarly to adults (i.e., they demonstrate as much inhibition of irrelevant items as do adults; Pritchard & Neumann, 2004).

The results of these studies highlight the importance of designing appropriate tasks in developmental research; certainly questions about the maturation of selective attention systems are tractable—with sensitive measurement tools. Many of these developmental studies, particularly those that have employed more traditional tasks, may have inadvertently confounded or conflated at least two aspects of selective attention: the initial selection of the to-be-attended channel and the subsequent perception and further processing of stimuli within (and outside of) that channel. The results from the more child-accessible paradigms that provide support for selection suggest that some of the effects of attention on perception and further processing of stimuli may be remarkably mature in very young children. Reports of poor selective attention skills in older children may thus be a reflection of broad, inflexible, or poorly tuned selection criteria in children rather than a lack of differential processing for attended and unattended items after that selection has been made. There is some behavioral evidence to support this hypothesis: on visual attention tasks, 5- and 8-year-olds benefit more than adults from cues directing their attention to the correct items (Heinbuck & Hershberger, 1989).

Employing neurocognitive measures in addition to behavioral measures may help to clarify what sorts of attentional skills are developing when. There is a lengthy history of event-related potentials (ERPs) being used to determine the stages at which selective attention affects processing in adults. In a classic ERP study of selective attention, adult listeners were asked to attend to one ear to detect rare high-frequency tones in rapid series of standard and target tones presented to both ears (Hillyard, Hink, Schwent, & Picton, 1973). Standard tones presented to the attended ear elicited larger N100s (negativity between 80 and 120 ms) than the same tones when unattended. Targets presented to the attended ear elicited larger P300s (positivity between 250 and 400 ms) than unattended targets. The finding that some portion of the attention effect mirrors the distribution of underlying ERP components suggests that attention modulates exogenously driven neural activity. However, attention effects in other time windows can have distributions distinct from the sensory ERP responses (Hansen & Hillyard, 1980). These effects are considered to index additional endogenous processing of attended stimuli rather than a simple gating of sensory information like that indexed by the amplitude of the N100 (Hansen & Hillyard, 1980). Since the initial report by Hillyard et al. (1973), this classic dichotic listening paradigm has been adapted to test many specific hypotheses about the neural systems important in selective attention, the timing of selective attention, and the impact of selective attention on the processing of syllables (Hink, Hillyard, & Benson, 1978), linguistic stimuli that vary by different features (Hansen, Dickstein, Berka, & Hillyard, 1983), and irrelevant probe stimuli that share many selection criteria with attended items (Hink & Hillyard, 1976).

A few similar ERP studies have been conducted with children over 5 years of age. Using a dichotic listening paradigm, Berman and Friedman (1995) showed that when 8-year-old, 14-year-old, and adult listeners attended to either specific pitch ranges or specific syllables to detect longer duration targets while ignoring other stimuli, a negative attention effect was evident between about 200 and 400 ms in all groups. However, the amplitude of this attention effect increased and its latency decreased from childhood to adulthood. In a cross-modal paradigm, children as young as 6 years old showed a larger negativity in response to auditory stimuli when they attended to the auditory as opposed to the visual modality, with the latency of this attention effect decreasing to adult levels by the age of 8 (Satterfield, Schell, Nicholas, Satterfield, & Freese, 1990). In a less canonical paradigm, listeners ages 8–22 were asked either to read a book or to actively attend to a rapid series of standard and rare tones. Typical auditory onset responses (P1, N1, P2, N2, and P3) were reported, but there was no evidence of a negative processing difference in children younger than 17 years of age (Oades, Dittmann-Balcar, & Zerbin, 1997). Overall, it appears that ERP selective auditory attention effects can be elicited in children at least as young as the age of 6 under certain conditions, consistent with the behavioral findings reviewed above.

In a review of both behavioral and ERP studies of the development of selective attention, Ridderinkhof and van der Stelt (2000) proposed that the abilities to select among competing stimuli and preferentially process more relevant information are essentially available in very young children, but that the speed and efficiency of these behaviors and the systems contributing to these abilities improve as children develop. To test this hypothesis more directly, the ERP paradigm employed by Hink and Hillyard (1976) was adapted to make dichotic listening more interesting and engaging for 6- to 8-year-old children (Coch, Sanders, & Neville, 2005). When these listeners were asked to selectively attend to one of two simultaneously presented stories that differed in position (left/right), voice (male/female), and content, children as young as age 6 years showed an auditory selective attention effect on ERPs to probe stimuli with similar onset latency to that observed in adults (100 ms). This finding suggests that, if given strong attentional cues, children as young as 6 years old can selectively attend to auditory information and that the nature and timing of these effects on processing auditory information are similar to those found in adults. Interestingly, the children in this study did not show the typical negative ERP attention effect; instead, irrelevant probe stimuli presented at the same location as the attended story elicited a larger positivity than those sharing the location of the unattended story. Some indication of a similar positive processing difference for the youngest children among 5-, 7-, and 9-year-olds in another selective attention study can be found in data presented in a figure but not otherwise analysed or discussed (Bartgis, Lilly, & Thomas, 2003, Figs. 1 and 2). Positive attention effects in children may also relate to the positive mismatch response reported in other studies with young children (Kushnerenko, Ceponiene, Balan, Fellman, & Näätänen, 2002; Maurer, Bucher, Brem, & Brandeis, 2003).

The results of these studies raise an important issue concerning ERP measures of auditory selective attention effects in young children: to accurately interpret attention effects as modulations of exogenously driven components or added endogenous components, it is necessary to understand the development of the basic underlying auditory evoked potentials (AEPs). Several studies have compared the AEP response to clicks or simple tones preceded by silence in children and adults. Although the distinct positive-negative-positive oscillations (P1, N1, P2) recorded from adults can be identified in at least some children as young as 6 years of age, P1 and N1 responses do not achieve mature amplitudes, latencies, or distributions until close to 20 years of age (Albrecht, Suchodoletz, & Uwer, 2000; Bruneau, Roux, Guérin, Barthélémy, & Lelord, 1997; Martin, Barajas, Fernandez, & Torres, 1988; Ponton, Eggermont, Khosla, Kwong, & Don, 2002; Ponton, Eggermont, Kwong, & Don, 2000). With an increased latency of the first positive component in the waveform and little or no N100 apparent until after the age of 12 (Ponton et al., 2002; Ponton et al., 2000), it could be expected that young children would show a broad positivity rather than an N100 at the onset latency of auditory selective attention effects, as described above (Coch et al., 2005). Moreover, there is some evidence that the impact of a crowded auditory environment (as in these complex dichotic listening paradigms) differs in young children and adults. In an

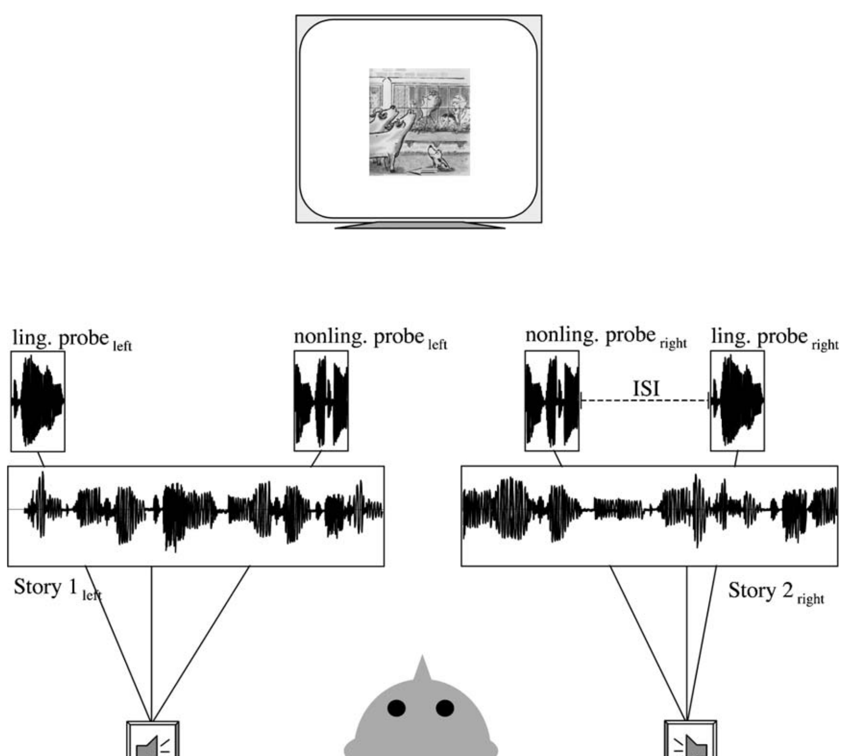

Fig. 1. Children and adults attended to an auditory story distinguished from a simultaneously presented second story by location, voice, and content. Images corresponding to the attended story were presented on a computer monitor and probe stimuli were embedded in both the attended and unattended stories.

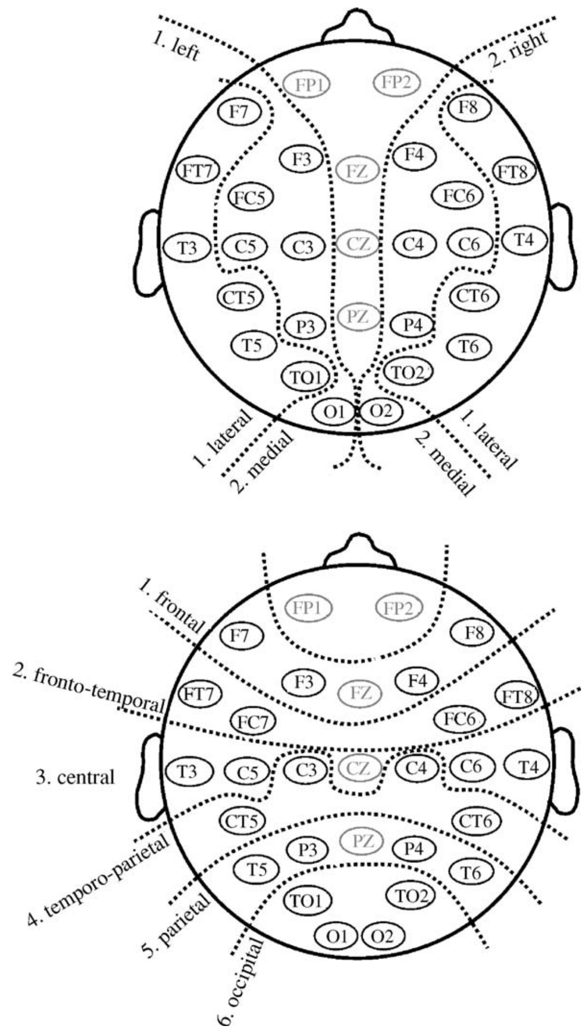

Fig. 2. The approximate locations of 29 scalp electrode sites. Dashed lines indicate which sites were included in the different levels of electrode position ANOVA factors: Hemisphere (left/right), Laterality (lateral/medial), and Anterior/Posterior (six levels from front to back). Electrode sites excluded from analysis are shown in grey.

MEG study with children ages 3 months to 15 years and adults, the age at which an adult-like N1m (magnetic equivalent of the N100) emerged was older with shorter interstimulus intervals (Paetau, Ahonen, Salnonen, & Sams, 1995); similar effects have been reported in ERP studies (Ceponiene, Cheour, & Näätänen, 1998).

Considering both the evidence for extended development of the AEP (P1, N1, and P2) and the complexity and rapid presentation of stimuli in auditory selective attention paradigms suitable for young children, it can be expected that the ERPs at a specific latency might be very different for young children and adults. However, it is not yet clear how immature AEPs (i.e., a broad positivity) might interact with potentially more mature ERP attention effects, particularly in very young children. One possibility is that an adult-like processing negativity (Nd) might be superimposed on children's AEPs, as reported for older children (Berman & Friedman, 1995; Satterfield et al., 1990). Alternatively, AEP amplitude in children might be modulated by selective attention in a manner similar to that in adults, resulting in larger responses to attended than unattended stimuli reflected in an Nd in adults but a positive processing difference in children (Coch et al., 2005). From the few studies available it might be hypothesized that there is a developmental progression from attentional modulation of a positivity in very young children to a superimposition of an adult-like Nd on that positivity in older children to a full-fledged, adult-like Nd in older adolescents.

In the present study, we explored the early development of these attentional and perceptual systems by modifying the procedure employed previously with 6- to 8-year-olds (Coch et al., 2005) to engage even younger children. As in the previous study, multiple, redundant attention cues were employed to direct attention to one of two simultaneously presented auditory stories. Children and adults were informed of the location the attended story would be presented from, the voice the attended story would be read in, and the topic of the story they should attend. The present study also used images that corresponded only to the attended story as an additional cue and multiple, related, shorter stories to help listeners sustain attention. We predicted that under these conditions of redundant attention cues and entertaining stimuli, children as young as 3 years old could successfully selectively attend to one story and that the effects of this selective attention on the processing of irrelevant probe stimuli would be an increase in the amplitude of the neural responses to probes from the attended story. More specifically, we hypothesized that probe stimuli would elicit a broad positivity similar to that found in older children and that attention would modulate this positivity such that a comparison between probes played from the attended and unattended sides would yield a positive processing difference.

2. Methods

2.1. Participants

The final sample included 13 adults between the ages of 18 and 35 years (eight women), 14 children between the ages of 6 and 8 years (range = 74–106 months, mean = 87 months [7 years, 3 months], seven girls), and 39 children between the ages of 3 and 5 years (range = 40–71 months, mean = 57 months [4 years, 9 months], 21 girls). All participants were right-handed (Oldfield, 1971), monolingual English speakers with no history of neurological or language disorders. The volunteers were paid for their time. The socio-economic status of the adults and the children's families ranged from lower middle to upper middle class with an average of middle class for all groups on the Hollingshead Index of Social Position (Hollingshead, 1975). On average, receptive composite language scores on the CELF (Semel, Wiig, & Secord, 1995) were in the 61st percentile for 6- to 8-year-olds (S.D. = 0.26, range = 0.25–0.99). Receptive language scores for the 3- to 5-year-olds on the Preschool CELF (Wiig, Secord, & Semel, 2004) were in the 66th percentile (S.D. = 0.23, range = 0.19–0.99).

This final sample was selected from a larger data set including 18 adults, 25 6- to 8-year-olds, and 55 3- to 5-year-olds. Participants were included in the final analyses only if they met the electrophysiological criteria described below and if the conditions selected for their experimental session could be counterbalanced within groups. Data from participants who were judged to have failed to attend to the correct story by the experimenter were excluded (0 adults, one 6- to 8-year-old, four 3- to 5-year-olds). In addition, only participants with an adequate number of trials (>40) in each condition of interest after artifact rejection were included. This criterion eliminated data from one adult, three 6- to 8-year-olds, and seven 3- to 5-year-olds. To roughly balance the number of children in each age group who began attending to the left and right sides, attended the female and male voice, and attended each of the two stories, data from seven 6- to 8-year-olds and five 3- to 5-year-olds were excluded from analyses; exclusion within each group was determined randomly. All adults began by attending to the left side (four right-start adults were excluded) with an equal number attending the female and male voice and each of the stories.

2.2. Stimuli

Four stories from the *Blue Kangaroo* series (Clark, 1998, 2000, 2002, 2003) and four from the *Harry the Dog* series (Zion & Graham, 1956, 1960, 1965, 1976) were digitally recorded (16 bit, 44.1 kHz) by both a male and female speaker. The stories were read in a child-directed manner at a normal speaking rate. Pauses were edited such that they did not exceed 1 s in order to lessen the opportunity for attention switches to the other channel and to equate the length of pairs of stories. The average amplitude of each story was equated and high amplitude noise created by bursts of airflow was deleted. Following this editing, one story from each series read by a male and female voice was pasted into a stereo file such that each story read in a male and female voice appeared once in the left channel and once in the right channel to create 32 stereo files (four stories × two series × two voices × two channels). Each stereo file was 2.5–3.5 min in length. The stories were presented at an average of 60 dB SPL (A-weighted).

Two probe stimuli were created by digitizing a token of the syllable *ba* spoken in a female voice (different from the female storyteller) and scrambling the order of 15–20 ms segments of that token to create a nonlinguistic sound with similar acoustic characteristics. The two probes were 100 ms in length, could be played in either the left or right channel, and were presented at 70 dB SPL.

Color pictures from the eight stories were scanned and edited. Pictures were cropped and reduced in size such that the image presented on the computer monitor directly in front of the participant subtended no more than 5° of vertical and horizontal visual angle. Fifteen to 20 images were selected from each story and presented for 5–15 s at points relevant to the content of the story. Additionally, a small arrow pointing to the left or right, indicative of the attended side, was superimposed at the bottom of each image.

2.3. Procedure

The procedure for this study (Fig. 1) was approved by the departmental experiment review board and the university's human subjects compliance office. The paradigm was similar to that previously designed for 6- to 8-year-old children (Coch et al., 2005) with a few notable exceptions. The stories were selected for their easier vocabulary and appeal to younger children. The experiment was conducted in four shorter (3 min) blocks rather than one longer (10 min) block. This change helped to focus the attention of younger children in several ways: they were given breaks more frequently and after shorter amounts of time, the experimenter could confirm that children were attending to the correct story more frequently, and the experimenter could discuss what the child should attend to next before every attention switch. Further, engaging images corresponding to the attended story were employed to both make the experience more entertaining and provide an additional attention cue. Other procedures were similar to those used in the previous study (Coch et al., 2005) and are described briefly here.

After explaining the procedures to adults or parents and children and addressing any questions, adults and parents signed a consent form. When the apparatus needed to record EEG was in place (described below), participants were seated in a comfortable chair in an electrically shielded, sound-attenuating booth. One speaker was placed 90° to the left of the subject and a second 90° to the right at equal distances. A computer monitor was positioned 57 inches in front of the participant. A practice session preceded the actual test session, and instructions were given both as part of the practice and by an adult experimenter seated either beside each child in the booth or, for adult participants, outside the booth. Listeners were instructed to pay attention to the story played from one speaker while ignoring the story presented over the other speaker. Participants were told whether the attended story would be told by a male or female speaker, that the arrows presented on the screen in front of them would point to the side they should be listening to, that the pictures on the screen in front of them would correspond to the attended story, and the general topic of the story to which they should listen. They were also told that unrelated 'buzzes' and 'bas' would be presented but could be ignored. Immediately before a set of stories began, participants were reminded to listen carefully to the story from a specific side, voice, and topic to be able to answer questions about that story. They were asked to look straight ahead at the pictures presented on the computer monitor, to avoid leaning towards either speaker, and to remain relaxed and still for the length of the story.

Three seconds after the stories began and images corresponding to the attended story appeared on the screen, the series of probe stimuli was introduced. An equal number of probe types (nonlinguistic and linguistic) were presented from each speaker (attended and unattended sides) with three different inter-stimulus intervals (200, 500, and 1000 ms).

After the presentation of a single set of stories, children (and five of the 13 included adults) were asked three two-choice questions about the attended story to further encourage their focused attention. After providing an answer or stating that they did not know, participants were told that they would hear another story concerning the same characters and read in the same voice. This procedure was repeated two more times until participants had listened to all four stories from the same series and answered 12 questions about the attended stories. At the end of all four stories, participants were also asked one general question about the unattended story. During the first and last pairs of stories participants attended to one side and during the second and third pairs the other side. All adults began by attending to the left side, whereas only half the children began by attending to the story presented on the left. A total of 240 attention probes were presented on the attended side and 240 on the unattended side across the duration of the experiment. For the duration of the experiment, adults were monitored through an intercom system and video camera and children were additionally monitored by an experimenter seated in the testing booth to insure that participants remained an equal distance from the two speakers.

2.4. ERP recording and analysis

Electroencephalogram (EEG) was recorded from 29 tin electrodes mounted in an elastic cap (Electro-Cap International). Electrodes were also placed beneath the lower right eye and at the outer canthi of the left and right eyes to monitor eye movements. During recording, each scalp electrode was referenced to the right mastoid; data were re-referenced to the averaged mastoids during off-line processing. Eye electrode impedances were maintained below 10 kΩ s and mastoid and scalp electrodes below 5 kΩ s.

EEG was amplified with Grass 7P511 amplifiers (bandpass 0.01–100 Hz) and digitized on-line (sampled every 4 ms). Off-line, separate ERPs to the four types of probe stimuli (attended/unattended × nonlinguistic/linguistic) were averaged for each subject at each electrode site over a 500 ms post-stimulus onset epoch, using the 100 ms immediately before stimulus onset as the baseline. A 60 Hz digital filter was applied to reduce electrical noise in the data. Trials contaminated by eye movements or muscle activities were not included in analyses. Limits on the maximum allowable amplitude change during a trial were determined for each participant by examining individual trials. The smallest change in amplitude judged to have been recorded during a blink by shape in EOG electrodes and reversal in polarity above and below the eye, during a horizontal eye movement by shape and distribution, and during movement by disruption across electrodes were selected as cutoffs to provide highly conservative artifact rejection. A criterion of a minimum of 40 artifact-free trials in each condition was imposed, but most participants had over 100 clean trials in each of the four conditions (Table 1).

Table 1
Number of included trials for adults and children by condition

Condition	Adults	6- to 8-year-olds	3- to 5-year-olds
Nonlinguistic probes			
Attended	191 (9)	157 (18)	156 (24)
Unattended	190 (11)	156 (17)	158 (24)
Linguistic probes			
Attended	191 (10)	156 (18)	156 (22)
Unattended	193 (11)	158 (19)	157 (21)

Note: Mean number of trials. Standard Error shown in parentheses.

Responses to nonlinguistic and linguistic probes that were superimposed on the attended and unattended stories were averaged separately. For adults, the peaks elicited by nonlinguistic probes were measured using local peak amplitude in three time windows: positive peak 50–150 ms (P1), negative peak 100–200 ms (N1) and positive peak 250–350 ms (P2). Local peak amplitudes were measured at all scalp electrode sites. A more sustained component was observed between 300 and 450 ms; mean amplitude was measured within this time window. For the linguistic probes, P1 amplitude was measured between 50 and 150 ms. N1 was characterized by measuring mean amplitude and local peak amplitude between 100 and 250 ms. A longer time window was selected to measure N1 amplitude to the linguistic probes based on the observably distinct morphology of this component for the two types of probes. As with the nonlinguistic probes, mean amplitude was also measured for the 300–450 ms time window. For children, the attention probes elicited a broad positivity that did not show a clear peak in some individual participant data. The attention effects in children were indexed with mean amplitude measures for the 100–200 ms, 200–300 ms, and 300–450 ms epochs. All measures taken across 24 electrode sites (Fig. 2) were subjected to a repeated measures ANOVA with the following four factors: Attention (attended/unattended), Electrode Hemisphere (left/right), Electrode Laterality (lateral/medial), and Anterior/Posterior Electrode Position (six levels). The distributions of attention effects and components were compared by entering attention effect measures (attended–unattended) at each electrode site and component measures into four-way ANOVAs: Measurement (attention effect/component), Hemisphere, Laterality, and Anterior/Posterior. Greenhouse-Geisser corrections were applied to all contrasts including factors with more than two levels.

3. Results

3.1. Adults: nonlinguistic probes

Although the two simultaneously presented stories resulted in almost continuous sound, the onset of nonlinguistic probe stimuli elicited typical auditory evoked potentials in adults as shown in Fig. 3. An early positive component (P1) peaking around 90 ms was largest at medial and anterior electrode sites (Laterality: $F(1,12) = 60.26$, $p < 0.001$, Anterior/Posterior: $F(5,60) = 23.45$, $p < 0.001$, Laterality × Anterior/Posterior: $F(5,60) = 19.93$, $p < 0.001$), but was not affected by attention (p's > 0.40, latency: M attended = 89 ms, M unattended = 90 ms). The first negative peak (N1) measured between 100 and 200 ms peaked around 125 ms and was also larger over anterior and right medial areas (Laterality: $F(1,12) = 3.62$, $p = 0.081$, Anterior/Posterior: $F(5,60) = 5.51$, $p = 0.019$, Hemisphere × Laterality: $F(1,12) = 4.68$, $p = 0.051$). Although the overall attention effect on the N1 was not significant, since many previous studies report that attended sounds elicit larger N1s than unattended sounds we explored the attention by electrode site interactions (Attention × Anterior/Posterior: $F(5,60) = 4.59$, $p = 0.016$, Attention × Hemisphere × Laterality × Anterior/Posterior: $F(5,60) = 2.28$, $p = 0.096$). This further analysis revealed a trend towards an attention effect in the expected direction (larger N1s for attended stimuli) at three central, right medial sites (FC6, C6, C4; $F(1,12) = 3.71$, $p = 0.078$). There was no evidence of differences in N1 latency by attention (M attended = 123 ms, M unattended = 127 ms) nor between the distribution of the N1 component and the attention effect on the N1 peak amplitude (p's > 0.40).

Following the N1, a second positivity (P2) was elicited that peaked around 190 ms. The P2 was largest at anterior and medial electrode sites (Laterality: $F(1,12) = 53.14$, $p < 0.001$, Anterior/Posterior: $F(5,60) = 8.95$, $p = 0.004$, Laterality × Anterior/Posterior: $F(5,60) = 21.91$, $p < 0.001$). Attended stimuli also elicited larger P2s over anterior and medial regions (Attention × Laterality: $F(1,12) = 15.22$, $p = 0.002$, Attention × Laterality × Anterior/Posterior: $F(5,60) = 2.99$, $p = 0.037$, Attention effect at F3, F4, FC5, FC6, C5, C6, C3, and C4: $F(1,12) = 6.44$, $p = 0.026$). The latency of this component did not differ by attention condition (M attended = 193 ms, M unattended = 181 ms). Similar to the N1 attention effect, the distributions of the P2 and the attention effect on the P2 did not differ (p's > 0.40). No attention effects were found in the later time window (mean amplitude 300–450 ms) in adults for the nonlinguistic probes (all p's > 0.30).

3.2. Adults: linguistic probes

In the adults, the linguistic attention probes elicited a P1 followed by a more sustained N1 (Fig. 3). Similar to the nonlinguistic probes, the P1 in response to the linguistic probes peaked around 90 ms, was larger over anterior and medial areas (Laterality: $F(1,12) = 44.28$, $p < 0.001$, Anterior/Posterior: $F(5,60) = 24.51$, $p < 0.001$, Laterality × Anterior/Posterior: $F(5,60) = 13.41$, $p < 0.001$), and its amplitude and latency were not significantly modulated by attention (latency: M attended = 89 ms, M unattended = 91 ms). The N1 to linguistic probes peaked around 210 ms (M attended = 212 ms, M unattended = 206 ms) and was also largest over anterior and medial regions (Laterality: $F(1,12) = 63.95$, $p < 0.001$, Anterior/Posterior: $F(5,60) = 2.87$, $p = 0.022$, Laterality × Anterior/Posterior: $F(5,60) = 18.71$, $p < 0.001$). Attention resulted in larger N1s over anterior and medial regions (Attention × Laterality: $F(1,12) = 9.07$, $p = 0.011$, Attention × Anterior/Posterior: $F(5,60) = 2.56$, $p = 0.093$, Attention × Laterality × Anterior/Posterior: $F(5,60) = 3.31$, $p = 0.039$, Attention at medial sites: $F(1,12) = 4.38$, $p = 0.058$). This effect was also evident in mean amplitude measures for the 100–250 ms epoch (Attention × Laterality: $F(1,12) = 9.95$, $p = 0.008$, Attention × Anterior/Posterior: $F(5,60) = 2.82$, $p = 0.089$, Attention × Laterality × Anterior/Posterior: $F(5,60) = 4.44$, $p = 0.015$). The attention effect on the N1 did not differ in distribution from the N1 (p's > 0.40). Attention also influenced AEPs in the later time window (Figs. 3 and 6) between 300 and 450 ms such that linguistic probes played from the attended side elicited a larger negativity over medial regions (Attention × Laterality: $F(1,12) = 30.01$, $p < 0.001$, Attention × Laterality × Anterior/Posterior: $F(5,60) = 7.60$, $p < 0.001$, Attention at F3, F4, C3, C4, P3, and P4: $F(1,12) = 5.33$, $p = 0.040$).

3.3. Six- to 8-year-olds: nonlinguistic probes

The attention probes elicited responses with a very different morphology in children as compared to adults. Unlike the P1–N1–P2 complex observed for adults, in children the probes elicited a broad positivity in the 100–200 ms epoch (Fig. 4). This positivity was largest at anterior and right medial electrode sites (Laterality: $F(1,13) = 48.46$,

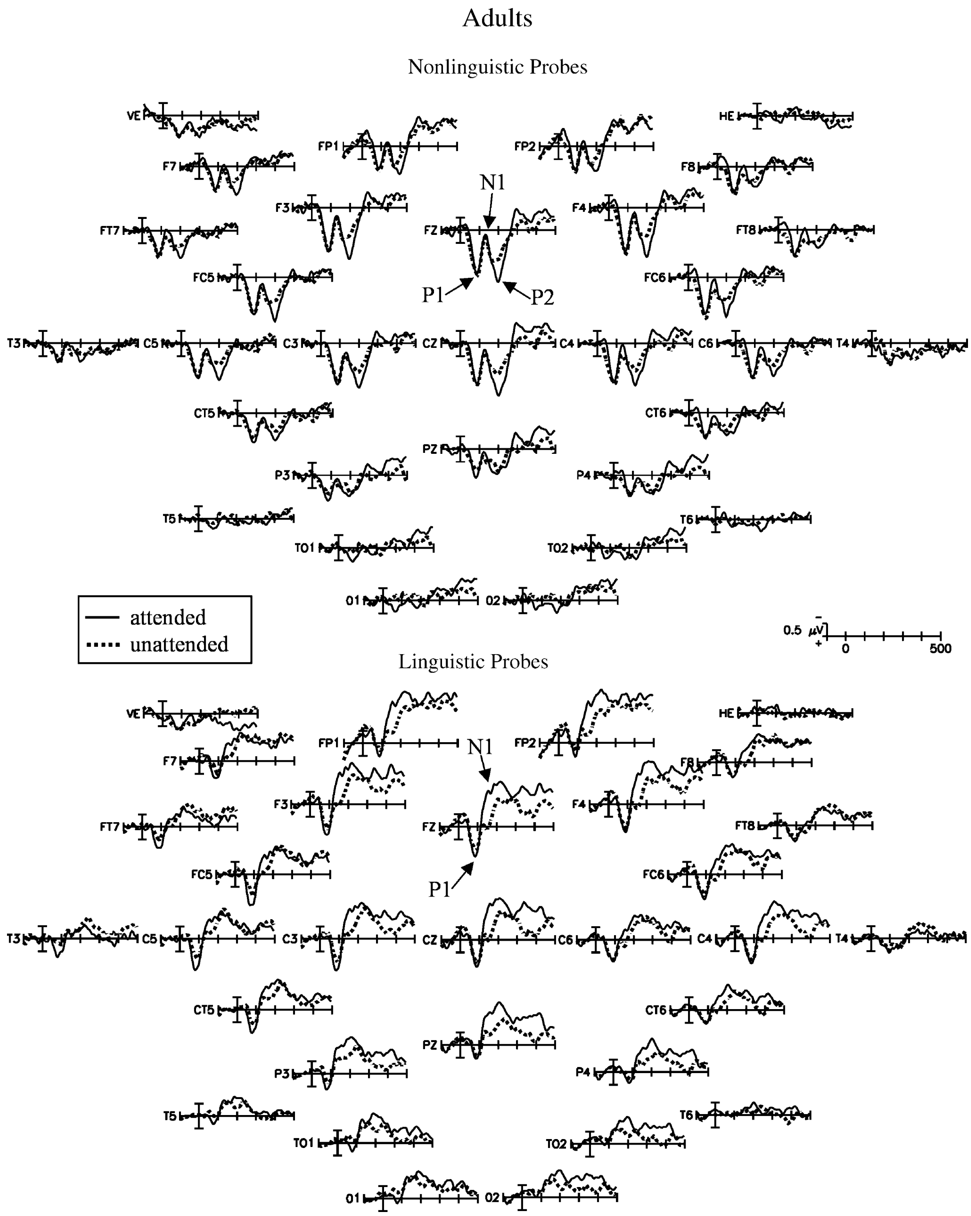

Fig. 3. In adults, ERPs elicited by nonlinguistic (top) and linguistic (bottom) probe stimuli presented from the same location as attended (solid lines) and unattended (dashed lines) stories. Nonlinguistic probes elicited distinct P1, N1, and P2 peaks. Both the N1 and P2 were larger in amplitude for nonlinguistic probes from the attended side. Linguistic probes elicited typical P1 and N1 auditory onset components, and the N1 was modulated by attention. Additionally, for linguistic probes, attention affected ERP amplitude in the later 300–450 ms time window.

$p < 0.001$, Anterior/Posterior: $F(5,65) = 19.07$, $p < 0.001$, Laterality × Anterior/Posterior: $F(5,65) = 31.69$, $p < 0.001$, Hemisphere × Laterality × Anterior/Posterior: $F(5,65) = 3.60$, $p = 0.017$). In 6- to 8-year-old children, attention modulated the amplitude of this positivity such that attended nonlinguistic probe stimuli elicited a larger *positivity* between 100 and 200 ms ($F(1,13) = 5.17$, $p = 0.041$). The attention effect had an anterior and right medial distribution similar to the distribution of the positive component itself (Attention × Anterior/Posterior: $F(5,65) = 3.22$, $p = 0.077$, Attention × Hemisphere × Anterior/Posterior: $F(5,65) = 3.39$, $p = 0.047$, Attention × Laterality × Anterior/Posterior: $F(5,65) = 3.64$, $p = 0.015$). No significant differences were found between the distribution of the positive component and the attention effect (p's > 0.40). The attention effect did not continue into the 200–300 ms time window (p's > 0.30), nor were attention effects found between 300 and 450 ms (p's > 0.40).

3.4. Six- to 8-year-olds: linguistic probes

Unlike in adults, the nonlinguistic and linguistic probes elicited similar AEPs in 6- to 8-year-olds: a broad positivity peaking around 150 ms (Fig. 4). The positivity elicited by the linguistic probes was largest over anterior, medial, and right regions (Hemisphere: $F(1,13) = 3.99$, $p = 0.067$, Laterality: $F(1,13) = 5.73$, $p = 0.032$, Anterior/Posterior: $F(5,65) = 27.92$, $p < 0.001$, Laterality × Anterior/Posterior:

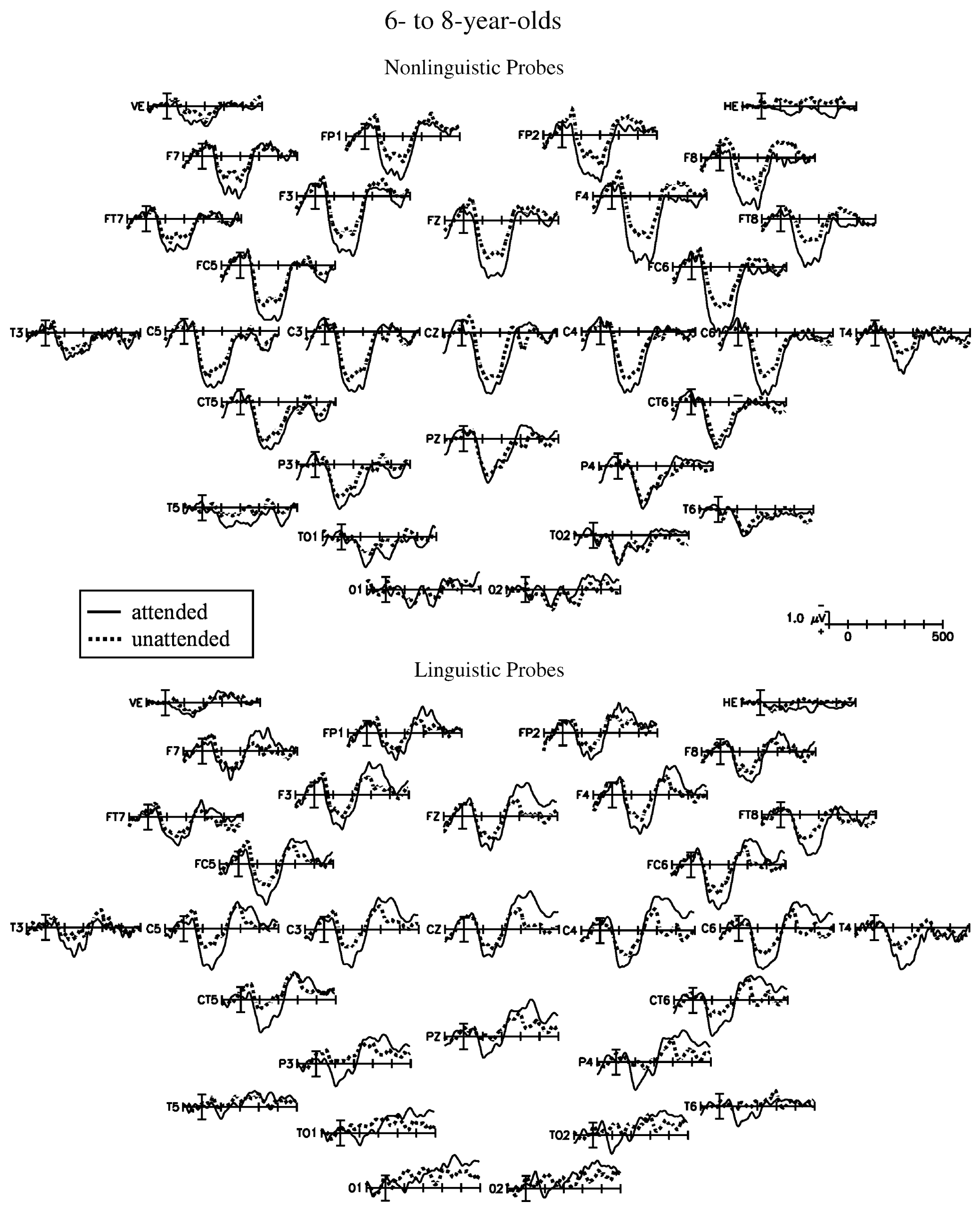

Fig. 4. In 6- to 8-year-old children, ERPs elicited by nonlinguistic (top) and linguistic (bottom) probe stimuli presented from the same location as attended (solid lines) and unattended (dashed lines) stories. Both types of probes elicited a single broad positivity during the first 300 ms after probe onset. Attention resulted in increased amplitude of this positive component (i.e., probes from the attended side elicited more positive ERPs) between 100 and 200 ms for both probe types. Additionally, linguistic probes from the attended side elicited more negative responses between 300 and 450 ms.

$F(5,65)=8.01$, $p=0.001$). The positivity was larger in amplitude for linguistic probe stimuli played from the attended side compared to the same stimuli played from the unattended side ($F(1,13)=8.06$, $p=0.014$). The attention effect showed a medial and right distribution similar to the distribution of the positivity itself (Attention × Hemisphere × Laterality: $F(1,13)=13.18$, $p=0.003$). The distributions of the positive component and attention effect were not significantly different (p's > 0.30). There was little evidence of this positive attention effect in the following 200–300 ms window (Figs. 4 and 6), though a trend toward a negative attention effect was found (Attention × Laterality: $F(1,13)=3.16$, $p=0.099$, Attention × Hemisphere × Laterality: $F(5,65)=3.42$, $p=0.043$). Between 300 and 450 ms, attended linguistic probes tended to elicit a larger negativity ($F(1,13)=3.70$, $p=0.071$), an effect larger over right medial regions (Attention × Laterality: $F(1,13)=13.99$, $p=0.002$, Attention × Hemisphere × Laterality: $F(1,13)=4.71$, $p=0.049$, Attention × Laterality × Anterior/Posterior: $F(5,65)=3.65$, $p=0.011$).

3.5. Three- to 5-year-olds: nonlinguistic probes

The waveforms observed in 3- to 5-year-olds were similar to those of the older children in that they were characterized by a broad positivity between 100 and 200 ms (Fig. 5). In response to the nonlinguistic probes, this positivity was largest over right medial and anterior regions (Hemi-

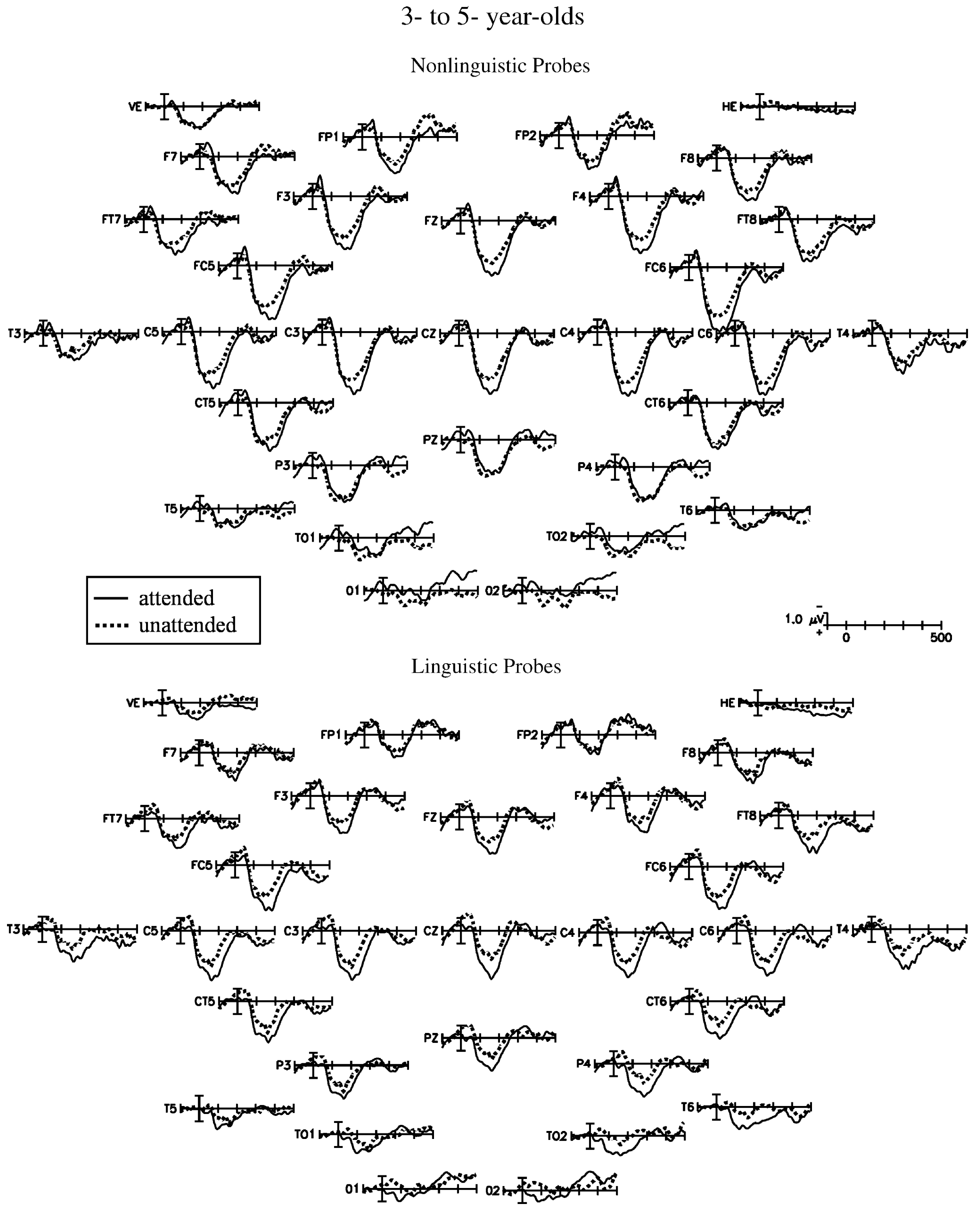

Fig. 5. In 3- to 5-year-old children, ERPs elicited by nonlinguistic (top) and linguistic (bottom) probe stimuli presented from the same location as attended (solid lines) and unattended (dashed lines) stories. Both types of probes elicited a single broad positivity during the first 300 ms as seen for the older children. Attention modulated this component such that probes from the attended side elicited a larger positivity than probes from the unattended side. For this younger group of children, the positive attention effect was prolonged into the 200–300 ms epoch for both probe types and into the 300–450 ms epoch for nonlinguistic probes. Similar to the other groups, there was some evidence of a negative attention effect between 300 and 450 ms in response to the linguistic probes.

sphere: $F(1,38) = 8.14$, $p = 0.007$, Laterality: $F(1,38) = 79.42$, $p < 0.001$, Anterior/Posterior: $F(5,190) = 65.29$, $p < 0.001$, Hemisphere × Anterior/Posterior: $F(5,190) = 8.93$, $p < 0.001$, Laterality × Anterior/Posterior: $F(5,90) = 72.75$, $p < 0.001$, Hemisphere × Laterality, Anterior/Posterior: $F(5,190) = 2.22$, $p = 0.086$). Similar to older children, the amplitude of this positivity was larger at anterior and medial sites between 100 and 200 ms in response to attended nonlinguistic probes (Attention × Anterior/Posterior: $F(5,190) = 5.41$, $p = 0.015$, Attention × Laterality × Anterior/Posterior: $F(5,190) = 5.23$, $p = 0.001$, Attention at anterior four rows: $F(1,38) = 5.77$, $p = 0.022$). There was no evidence for a difference in the distributions of the positive component and the attention effect (p's > 0.40). However, unlike in older children, this positive attention effect over anterior regions continued into the following 200–300 ms time window (Attention: $F(1,38) = 4.68$, $p = 0.037$, Attention × Anterior/Posterior: $F(5,190) = 4.35$, $p = 0.028$) (Figs. 5 and 6). Evidence of this positive attention effect over anterior regions remained in the 300–450 ms epoch as well (Attention × Anterior/Posterior: $F(5,190) = 5.57$, $p = 0.010$).

3.6. Three- to 5-year-olds: linguistic probes

Linguistic probes also elicited a broad positivity in children aged 3- to 5 (Fig. 5). This positivity was largest at

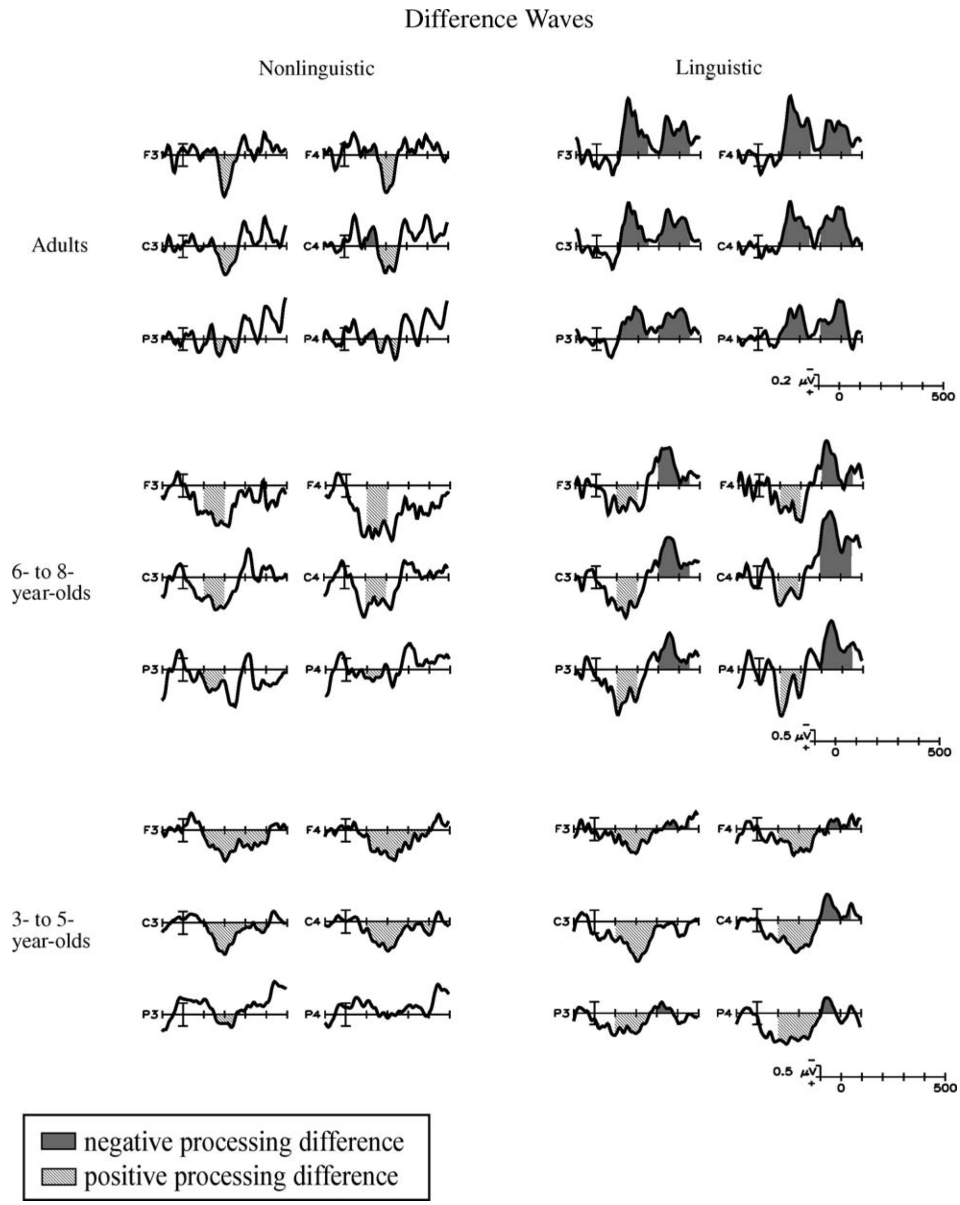

Fig. 6. Difference waves (attended–unattended) at six selected electrode sites for adults, 6- to 8-year-olds, and 3- to 5-year-olds. For all groups in response to both types of probe stimuli, attention increased AEP amplitude beginning around 100 ms after onset. In the youngest children (3- to 5-year-olds) this attention effect was prolonged. For the linguistic probes only, a greater negative attention effect was found for all groups in a later time window (300–450 ms).

right medial and anterior sites (Laterality: $F(1,38) = 36.82$, $p < 0.001$, Anterior/Posterior: $F(5,190) = 39.41$, $p < 0.001$, Hemisphere × Laterality: $F(1,38) = 9.13$, $p = 0.004$, Laterality × Anterior/Posterior: $F(5,190) = 41.28$, $p < 0.001$, Hemisphere × Laterality × Anterior/Posterior: $F(5,190) = 5.46$, $p < 0.001$). Attention modulated the positivity in this age group as well ($F(1,38) = 8.43$, $p = 0.006$) such that attended probes elicited a larger positivity. The attention effect, similar to the positivity itself, was largest over right medial regions (Attention × Hemisphere × Laterality: $F(1,38) = 6.80$, $p = 0.013$). The distributions for the component and attention effect did not differ (p's > 0.40). As it did for the nonlinguistic probes, the positive attention effect in 3- to 5-year-olds continued into the 200–300 ms time window ($F(1,38) = 8.50$, $p = 0.006$) (Figs. 5 and 6) with a similar right, medial distribution (Attention × Hemisphere × Laterality: $F(1,38) = 6.96$, $p = 0.012$). In response to the linguistic probes, the negative attention effect in the 300–450 ms time window found for adults and older children could also be seen at right medial and posterior sites in 3- to 5-year-olds (Attention × Laterality: $F(1,38) = 6.13$, $p = 0.018$, Attention × Hemisphere × Laterality: $F(1,38) = 8.03$, $p = 0.007$).

3.7. Behavioral questions

The primary goal of asking questions concerning the attended story was to provide an additional incentive for participants to follow instructions, and participants answers provided some indication of an ability to do so. Of the five adults who were asked questions, all five correctly answered the 12 questions concerning the attended story and only three correctly answered the single question about the unattended story. Six- to 8-year-old children performed significantly better than chance for questions on the attended story ($M = 10.8$ of 12 correct, S.E. = 0.24, $t(13) = 20.06$, $p < 0.001$) and no different from chance for the question about the unattended story ($M = 0.5$ of 1 correct, S.E. = 0.14). Three- to 5-year-olds were better than chance at responding correctly to questions on the attended story ($M = 9.31$ of 12 correct, S.E. = 0.21, $t(38) = 15.88$, $p < 0.001$), but were not as accurate as older children ($t(51) = 3.92$, $p < 0.001$). Performance for this group was also at chance for the question concerning the unattended story ($M = 0.49$ of 1 correct, S.E. = 0.08).

4. Discussion

The paradigm employed in this study involved an extremely dense auditory environment: two different stories presented simultaneously as continuous natural speech and two types of slightly louder, 100 ms duration probe stimuli presented with variable ISIs at an average of 1.5 probes per second. Even with a complex auditory scene, adults showed typical auditory onset ERP components in response to the probe stimuli. Additionally, adults were able to parse this auditory scene and selectively attend to only one of the stories. Data from this and a previous similar study (Coch et al., 2005) suggest that this general paradigm successfully elicits typical auditory selective attention ERP effects: a larger negativity between 100 and 200 ms in response to stimuli presented in an attended channel.

Importantly, children as young as ages 3- to 5 years were also shown to be able to selectively attend to a specific story in this complex auditory environment. By providing strong, redundant attention cues and age-appropriate, interesting stimuli, these young children were able to attend to relevant information and ignore other simultaneously presented stimuli that shared many characteristics with the attended information. Furthermore, the impact of this selective attention on perceptual processing as indexed by ERPs was similar to that in older children and adults. By 100 ms after stimulus onset, adults, 6- to 8-year-olds, and 3- to 5-year-olds all showed differential processing of irrelevant probe stimuli embedded in attended and unattended stories.

For the adults, the distribution of the early attention effects mirrored the distribution of the N1 component itself. The distributional similarity within the same time window is consistent with the hypothesis that these early attention effects index the modulation of exogenously driven auditory onset components as shown in previous studies with adults (e.g., Hansen & Hillyard, 1980). The later attention effect (300–450 ms) found only for the linguistic probes suggests that these stimuli uniquely elicited additional endogenous processing. The additional processing for linguistic probes likely relates to the degree of similarity between these probes and the narrative information to which participants were attending. That is, listeners were asked to attend to an auditory story presented from one side. Both nonlinguistic and linguistic probes presented from the same location as the attended story were considered to be attended as well and were as evidenced by the early attention effects. However, linguistic probes from the attended side shared more features with the attended story than did the nonlinguistic probes from the same side. The greater similarity between probe and attended channel may have resulted in additional processing specific to the linguistic probes.

Similar to a previous study (Coch et al., 2005), the auditory onset potentials evoked by linguistic and nonlinguistic probes differed: nonlinguistic probes elicited a sharply peaked N1 followed by a large P2 whereas linguistic probes elicited a more sustained N1 and a barely discernable P2. Although this difference in wave morphology likely reflects physical differences in the probes, the attention effects mirror the components. In both studies, the N1 attention effect is more pronounced and longer in duration for the linguistic probes. Indeed, the N1 attention effect for the nonlinguistic probes did not reach significance in the current study (likely due to too few adult participants). In contrast, the attention effect on the P2 component is much more pronounced for the nonlinguistic probes. The correspondence of amplitude, duration, and distribution of attention effects and underlying auditory onset components suggests that for adults in this paradigm, selective attention modulates existing AEPs (specifically N1 and P2) rather than introducing additional components.

One of the most striking observations from this study is that children showed a broad positivity rather than the adult positive-negative-positive ERP oscillation in response to auditory onsets in a dense auditory environment. Even though the N100 response has a long developmental time course, several studies examining the development of the N1 using clicks or tones presented in silence report that 6- to 8-year-olds show some indication of an N1 albeit with a different latency or distribution from that found in adults (Albrecht et al., 2000; Bruneau et al., 1997; Martin et al., 1988; Ponton et al., 2002; Ponton et al., 2000). However, in this study there was little evidence of an N1 in either group of children. One possible explanation for the lack of an N1 in 6- to 8-year-olds is that the N1 may be more refractory in this group than in adults (Ceponiene et al., 1998; Paetau et al., 1995). An immature, small amplitude, and highly refractory N1 in 6- to 8-year-olds might disappear entirely under conditions of an extremely dense auditory environment.

Similar to a previous report (Coch et al., 2005), in the current study auditory evoked potentials recorded from 6- to 8-year-olds indexed robust effects of selective auditory attention. The attention effect took the form of a larger positivity in response to probes embedded in the attended as opposed to the unattended story. As with adults, the attention effect began around 100 ms after onset of the attention probes and continued for at least 100 ms. Additionally, this early attention effect in 6- to 8-year-olds had a similar distribution to the broad positive component in the same time window. Thus, even though the early attention effects in adults and 6- to 8-year-olds were in many respects quite different, the effects for both groups can be characterized as an increase in amplitude of exogenously driven auditory onset components beginning around 100 ms after onset.

In the youngest group of children, the attention effect was also robust, began around 100 ms, and was positive in polarity. Unlike in older children, the attention effect in 3- to 5-year-olds was prolonged into the 200–300 ms time window. This may reflect longer processing times for the irrelevant probe stimuli in these younger children. However, there are several possible explanations for the absence of evidence for a positive attention effect between 200 and 300 ms for 6- to 8-year olds in the current study. First, with only 14 children in this group there may not have been enough statistical power to detect the smaller amplitude effect. Second, the shorter blocks of sustained attention and additional cue in the form of images corresponding to the attended story may have helped 6- to 8-year-olds to be more efficient in focusing their attention. This second possibility is supported by the findings from the previous study (Coch et al., 2005) in which the visual cues were less supportive and the positive processing difference extended at least until 250 ms in 6- to 8-year-olds.

Adults, 6- to 8-year-olds, and 3- to 5-year-olds shared another similarity in the ERP waveforms: a late negative polarity attention effect found for linguistic probes only. The difference in attention effects found for the nonlinguistic and linguistic probes is indicative of precise selection by the attention systems in all groups. In our previous study adults, but not 6- to 8-year-olds, showed attention effects with different distributions for the two types of probes (Coch et al., 2005). This result was used to argue that attentional selection in adults is more precise than that of 6- to 8-year-old children, consistent with many behavioral studies described in the introduction (e.g. Doyle, 1973; Hiscock & Kinsbourne, 1980; Pearson & Lane, 1991). However, just as previous behavioral studies have shown that with ample cues children can show adult-like selective attention abilities at earlier ages, the addition of engaging images related to the to-be-attended story may have helped the 6- to 8-year-olds and 3- to 5-year-olds in the current study to more finely tune their attention selection.

There are at least three possible explanations for the difference in polarity of the earliest attention effects between children and adults. First, children might employ wholly different attention systems, unrelated to those used by adults. However, the many similarities between child and adult attention effects, specifically the latency and similarities between component and attention effect distributions, lend support to other hypotheses. Second, it is reasonable to postulate that separate systems could affect the polarity of AEPs and attention effects in a similar manner. This argument is more parsimonious if a single neural maturation process plays a role in both systems. For example, different developmental time courses for different layers of cortex (Ponton et al., 2000) may contribute to differences in the polarity of both AEPs and attention effects in children and adults. A third hypothesis is that adults and children show the same modulation of exogenously driven auditory onset components resulting in a negative attention effect in adults and a positive attention effect in children younger than 8 years.

In adults, some studies have reported auditory selective attention effects that can be completely accounted for by modulations of auditory onset components (e.g., Hillyard et al., 1973) and others invoke new components added to the exogenously driven AEPs (e.g., Hansen & Hillyard, 1980). The differences in modulation of onset components and addition of new components are quite subtle in adult ERPs; the two outcomes are typically distinguished by small variations in distribution. However, the case may be very different in children if endogenous processing effects have the opposite polarity of exogenously driven onset components. Small differences in the experimental conditions such as the number and type of external cues may determine the polarity of selective attention effects in children. A similar distinction between modulation of auditory onset components and added components marking additional endogenous processing may explain discrepancies in the polarity of mismatch responses in children. The rare stimuli in auditory oddball paradigms with children have been reported to elicit negativities (adult-like MMNs) in some studies and positive deflections in others (Kushnerenko et al., 2002; Maurer et al., 2003).

Overall, this study shows that young children are able to selectively attend to auditory information and that the ways in which attention affects early neural processing are in many respects mature in children as young as 3 years old. Considering the potential importance of selective attention in the development of many perceptual and cognitive skills, it is reasonable to postulate that the ability to attend to specific information while ignoring competing information may begin to develop very early in life. However, there is also clear evidence that the ability to selectively focus attention with sparse exogenous cues continues to develop at least until adolescence. By recognizing both young children's capacity to selectively attend and the limits on the conditions under which they are successful in doing so, it may be possible to create policies and programs that build on children's underappreciated attentional skills.

Acknowledgements

This research was supported by NIH, NIDCD grant DC00481 to H.J.N. D.C was supported by NIH/NICHD grant HD08598, C.S by an NSF Graduate Research Fellowship, and L.D.S. by NIH/NIDCD DC005291. We also wish to thank the many researchers and technicians involved in collecting extensive behavioral and ERP data from young children: Annika Andersson, Paul Compton, Jessica Fanning, Petya Ilcheva, Brittni Lauinger, Nicole Makarenco, David Paulsen, Lisa Stewart, Ray Vukcevich, Brad Wible, and Yoshiko Yamada.

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