International Journal of Psychophysiology 95 (2015) 156–166

Contents lists available at ScienceDirect

International Journal of Psychophysiology

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

Atypical auditory refractory periods in children from lower socio-economic status backgrounds: ERP evidence for a role of selective attention

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ARTICLE INFO

Article history:
Received 15 September 2013
Received in revised form 13 June 2014
Accepted 29 June 2014
Available online 6 July 2014

Keywords:
Socioeconomic status
SES
Refractory periods
ERP
Attention
Auditory processing

ABSTRACT

Previous neuroimaging studies indicate that lower socio-economic status (SES) is associated with reduced effects of selective attention on auditory processing. Here, we investigated whether lower SES is also associated with differences in a stimulus-driven aspect of auditory processing: the neural refractory period, or reduced amplitude response at faster rates of stimulus presentation. Thirty-two children aged 3 to 8 years participated, and were divided into two SES groups based on maternal education. Event-related brain potentials were recorded to probe stimuli presented at interstimulus intervals (ISIs) of 200, 500, or 1000 ms. These probes were superimposed on story narratives when attended and ignored, permitting a simultaneous experimental manipulation of selective attention. Results indicated that group differences in refractory periods differed as a function of attention condition. Children from higher SES backgrounds showed full neural recovery by 500 ms for attended stimuli, but required at least 1000 ms for unattended stimuli. In contrast, children from lower SES backgrounds showed similar refractory effects to attended and unattended stimuli, with full neural recovery by 500 ms. Thus, in higher SES children only, one functional consequence of selective attention is attenuation of the response to unattended stimuli, particularly at rapid ISIs, altering basic properties of the auditory refractory period. Together, these data indicate that differences in selective attention impact basic aspects of auditory processing in children from lower SES backgrounds.

1. Introduction

A large literature documents the robust relationship between socio-economic status (SES) and academic outcomes (for reviews, see Brooks-Gunn and Duncan, 1997; Duncan et al., 1994). Whether assessed using school grades, standardized test scores, or graduation rates, children from lower SES backgrounds fare worse on average than their higher SES peers (Baydar et al., 1993; Liaw and Brooks-Gunn, 1994; Walker et al., 1994). More recently, research in cognitive science and cognitive neuroscience has focused on identifying particular cognitive skills and neural systems underlying these academic disparities (e.g., Noble et al., 2005, 2007; Stevens et al., 2009). The promise of these more focused investigations is twofold (for discussions, see Hackman and Farah, 2008; Neville et al., 2013a). First, this research can identify foundational systems that, if impaired, might have cascading consequences for performance on broad academic indicators (e.g., Noble et al., 2005; Stevens and Bavelier, 2012). Second, by identifying vulnerable foundational systems, interventions to reduce SES-related academic disparities can be developed that target these foundational systems (e.g., Neville et al., 2013b, targeting selective attention; Noble et al., 2012, targeting preschool preliteracy and math skills).

While previous research identifies aspects of attention and language as particularly vulnerable to SES-related disparities (Hackman and Farah, 2008; Hackman et al., 2010; Mezzacappa, 2004; Noble et al., 2005; Stevens et al., 2009), to date no research has examined SES-differences in more basic aspects of sensory processing. In the present study, we sought to investigate whether lower SES is also associated with differences in a basic aspect of auditory processing: the auditory neural refractory period, or reduced amplitude neural response at more rapid rates of stimulus presentation. We examined the auditory refractory period because it is a sensory-driven neural response that is associated with atypical language development (Neville et al., 1993; Stevens et al., 2012). The present study also sought to investigate whether any observed differences in auditory refractory period effects could be accounted for by manipulations of selective attention. This permitted a simultaneous investigation of both sensory-driven and top-down modulation of auditory processing in children from higher versus lower SES backgrounds.

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http://dx.doi.org/10.1016/j.ijpsycho.2014.06.017
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1.1. Auditory evoked potentials

Event-related brain potentials (ERPs) provide a unique window into the nature of basic auditory processing. With their exquisite temporal resolution, ERPs are ideal for characterizing the timecourse of processing, as well as the impact of experimental manipulations on different stages of processing. Moreover, as ERPs can be recorded noninvasively in infants and young children, the technique is particularly well suited for characterizing the development of auditory processing. We focus here on aspects of the auditory evoked potential arising from cortical activity during the initial few hundred milliseconds of auditory processing.

Morphologically, the auditory evoked potential shows developmental shifts from childhood to adulthood. In adults, the auditory evoked response is typically characterized by an initial positivity (P1) peaking ~50 ms after stimulus presentation, followed by an early negativity (N1) peaking ~100 ms after stimulus presentation (Ponton et al., 2000). The obligatory P1–N1 complex is sometimes followed by a second positivity and negativity (Ponton et al., 2000), though these later peaks are not observed with all auditory stimuli (Sanders et al., 2006). In contrast to the mature adult response, children's auditory evoked responses are typically dominated by a single broad positivity from ~50 to 200 ms after stimulus presentation, with little or no N1 apparent in this latency range until after age 12 (Albrecht et al., 2000; Ponton et al., 2000). Other studies report a delayed negativity in children as young as six years old, peaking closer to 300 ms post-stimulus onset (Coch et al., 2005b). Together, these studies indicate important development shifts in the morphology of the underlying auditory evoked response during maturation.

Further research has examined the effects of different experimental manipulations on early cortical evoked responses, and whether these effects are similar across development. In one experimental manipulation, the effect of rate of presentation is examined by varying the inter-stimulus interval (ISI) between successive stimuli. Among adults, N1 amplitude to auditory stimuli becomes smaller as rate of presentation increases (Budd et al., 1998; Coch et al., 2005b; Wang et al., 2004). The reduced amplitude is believed to reflect the reduced excitability of cortical neurons immediately following an action potential, or the effective processing rate of neurons (Budd et al., 1998; Gastaut et al., 1951). We will use the term ‘auditory refractory period’ to describe the amplitude reduction apparent at more rapid rates of stimulus presentation. While it is statistically impossible to demonstrate full neural recovery, studies of auditory refractory periods typically infer full neural recovery when no significant differences remain in the amplitude of the neural response to stimuli presented at increasing ISIs.

Interestingly, children show similar attenuation of the neural response with increasing rates of presentation, though these effects can be overlaid on a morphologically immature cortical response (Coch et al., 2005b; Rojas et al., 1998; Stevens et al., 2012). For example, when children show a broad positivity in response to auditory stimuli, this broad positivity is smaller in amplitude as rate of presentation increases (Stevens et al., 2012). Moreover, younger children also often exhibit larger refractory effects than adults, or refractory effects that persist at longer ISIs than in adults (Coch et al., 2005b; Rojas et al., 1998). In other words, with increasing age, the neural response appears to recover more quickly, whereas during development, children may require longer intervals between stimuli for the neural response to show full recovery. The reason for this longer recovery time in children remains unclear, however one contributing factor may involve longer neural recovery time when the neural response to stimuli is larger overall and/or longer in duration, as occurs in children's auditory evoked responses.

Cortical auditory evoked responses also vary with experimental manipulations of selective attention (for reviews, see Hillyard et al., 1987; Hopfinger et al., 2004). In a typical selective auditory attention paradigm, two streams of competing auditory input are presented simultaneously to separate ears, with participants monitoring one of the two streams for rare deviant stimuli. In adults, stimuli presented to the attended channel elicit larger N1s than the same stimuli when presented in the unattended channel (Hillyard et al., 1973). Further, as some portion of the cortical distribution of the attention effect mirrors the distribution of the underlying ERP components, attentional modulation appears to act at least in part as a gain control mechanism on input-driven neural activity.

To examine whether children show similar effects of selective attention on auditory processing, we have developed a child-friendly selective auditory attention ERP paradigm (Coch et al., 2005a; Sanders et al., 2006). In this paradigm, two stories are played simultaneously from speakers located to the left and right of the participant, who attends selectively to one of the two stories. ERPs are recorded to probe stimuli superimposed on both attended and unattended narratives. In this paradigm, both children and adults show clear effects of selective attention within 100 ms of processing: in adults, the N1 to probe stimuli in the attended channel is increased in amplitude, and in children as young as three years old, the broad positivity to probe stimuli in the attended channel is increased in amplitude (Coch et al., 2005a; Sanders et al., 2006).

Together, these studies paint a complex picture of the maturation of the neural circuitry supporting basic auditory processing. On the one hand, the basic morphology of the auditory evoked response shows a protracted time course of development. However, despite an immature morphology, the auditory system of children exhibits adult-like functional responses to some experimental manipulations. For example, as described above, with increasing rates of stimulus presentation, both children and adults show an attenuation of early neural responses. Similarly, with selective attention, both children and adults show an increase in the underlying neural response within 100 ms. Indeed, it is interesting to note that in both adults and children, the effects of selective attention and rate of stimulus presentation have complementary effects: whereas rapid rates of presentation effectively *dampen* the neural response, selective attention serves to *increase* the neural response. These findings indicate that basic auditory processing is influenced not only by developmental shifts in neural systems, but also by bottom-up stimulus attributes and top-down attentional control. However, as these studies were generally conducted with typically developing, higher SES samples, they do not elucidate whether or how these aspects of auditory processing are altered in special populations, including those from different SES backgrounds.

1.2. Auditory processing and language development

It has been proposed that higher-level functions including language comprehension depend critically on the integrity of basic auditory processing (Tallal, 1980, 2004; Tallal and Piercy, 1973). The relationship between basic auditory processing and language development has been illustrated most strongly in the case of Specific Language Impairment (SLI), a developmental disorder characterized by poor receptive language skills in the face of typical nonverbal intelligence (Leonard, 1998). For example, several studies have reported that at least some children with SLI have particular difficulty processing auditory information that is presented at rapid rates and/or that is distinguished on the basis of brief auditory cues (Tallal, 1980, 2004; Tallal and Piercy, 1973) (but see also Neville et al., 1993 showing deficits in a sub-sample of children with SLI, but no correlation between rapid auditory processing and receptive language scores). These perceptual deficits have been proposed to impair speech perception by disrupting the ability to form stable representations of some phonemes, such as /ba/ and /da/, which are differentiated only by cues occurring in the first 40 ms of stimulus onset. Indeed, it has been observed that some of the morphemes that are most problematic for children with SLI are also the least perceptually salient (Leonard, 1998), suggesting that subtle auditory processing deficits might render these forms more difficult to acquire.

A growing literature has further documented neurophysiological differences in basic auditory processing among children with SLI. For example, several ERP and magnetoencephalographic studies document that individuals with SLI show atypical neural responses to both linguistic and nonlinguistic auditory stimuli during the first few hundred milliseconds of processing, including delayed latencies, reduced amplitudes, and/or abnormal morphologies of the cortical evoked response (Bishop et al., 2007; Bishop and McArthur, 2005; McArthur and Bishop, 2004, 2005; Pihko et al., 2008). However, even when the morphology of the auditory evoked response is similar, children with SLI also exhibit atypical effects of experimental manipulations on early auditory evoked responses. For example, at least some children with SLI show greater vulnerability of the neural response with increasing rates of stimulus presentation, with the neural response less consistently or robustly representing stimuli when presented at rapid rates (Basu et al., 2010; Neville et al., 1993; Stevens et al., 2012). In the case of the auditory refractory period, specifically, children with SLI show more pronounced attenuation of the neural response at the most rapid rates of stimulus presentation (Neville et al., 1993; Stevens et al., 2012). Children with SLI also show differences in the effects of selective attention on neural processing (Shafer et al., 2005; Stevens et al., 2006). For example, we have shown, using our child-friendly ERP paradigm, that children with SLI do not show early attentional modulation of the neural response (Stevens et al., 2006). We have further shown that this effect is driven by a deficit in the increase to the neural response to stimuli in the attended channel (i.e., poor signal enhancement), as opposed to a difficulty in suppressing the neural response to unattended stimuli (i.e., poor distractor suppression).

To examine whether the attention deficits in children with SLI also influenced their auditory refractory period effects, we recently re-examined data from the same selective attention paradigm, but considered the ISI between successive probe stimuli, which was set at 200, 500, or 1000 ms (Stevens et al., 2012). We observed that children with SLI showed a reduced amplitude response compared to their typically developing peers for stimuli presented at the fastest, 200 ms ISI, but this effect could not be explained by and did not interact with the direction of selective attention. This suggested that, for children with SLI, early stages of auditory processing can be impacted by the rate of presentation and the direction of selective attention, but these effects are independent of one another. Thus, at least some children with SLI may be double-compromised, with deficits in both stimulus-driven responses to stimuli presented at rapid rates, and an inability to enhance the neural response endogenously through selective attention.

1.3. Auditory processing and SES

Despite advances in using non-invasive neuroimaging to characterize auditory processing, to our knowledge no research has explored differences in basic auditory processing in children from different SES backgrounds. In contrast, much early work on SES-related disparities focused on broad academic indicators, including graduation rates and standardized test scores (Baydar et al., 1993; Liaw and Brooks-Gunn, 1994; Walker et al., 1994). Over the past decade, some research has narrowed the focus of investigations to identify possible core systems that might influence performance on broad academic indicators. Two of the most robust findings are difficulties in aspects of language and attention (Hackman and Farah, 2008; Hackman et al., 2010; Mezzacappa, 2004; Noble et al., 2005; Stevens et al., 2009).

An emerging goal of research on SES-related disparities is developing and assessing interventions that can reduce achievement gaps (Neville et al., 2013b; Noble et al., 2012). By identifying specific cognitive and neural systems that are most vulnerable to SES, as well as the mechanisms whereby these systems are altered, targeted programs can be developed that address these vulnerable systems. For example, several studies suggest that language development is particularly vulnerable in children from lower SES backgrounds, and that differences in language development may be related in important ways to differences in the language input children receive (Hart and Risley, 1995; Hoff, 2003; Hurtado et al., 2008; Huttenlocher et al., 2002). Fewer studies have examined whether aspects of basic auditory processing, which may be important for supporting language development, provide another pathway whereby higher-level language processing might be altered. Previous research indicates that children from lower SES backgrounds show reduced effects of selective attention on neural processing (D'Angiulli et al., 2008; Stevens et al., 2009). Thus, similarly to children with SLI, children from lower SES backgrounds exhibit difficulty endogenously directing selective attention in ways that alter early stages of neural processing. However, in contrast to children with SLI, who show a specific difficulty in signal enhancement, children from lower SES backgrounds show specific difficulty in suppressing unattended information.

Thus, current research has begun to hone in on aspects of attention and language processing as core systems vulnerable in children from lower SES backgrounds. However, it is unclear whether more basic aspects of auditory processing, including stimulus-driven refractory period effects, also vary with SES background, or if differences only arise at higher-level stages of processing. One possibility is that children from lower SES backgrounds show atypical refractory effects, similar to those reported in children with SLI. If observed, such findings would suggest a possible basic auditory processing deficit that could compound the processing differences arising from deficits in selective attention. A second possibility is that children from lower SES backgrounds exhibit typical refractory period effects, suggesting similarities in basic auditory processing in children from different SES backgrounds. This would suggest that children from lower SES backgrounds show atypical neural responses only when selective attention must be endogenously directed to modulate processing, but that the basic refractory effects are similar across groups. Finally, a third possibility is that children from lower SES backgrounds show atypical refractory period effects, but only as a function of attention condition. If this pattern of results was observed, it would suggest that deficits in attention serve to alter the refractory properties of the auditory system, or the ability of the auditory system to function optimally with rapid rates of presentation.

1.4. Goals & overview of the present study

The present paper offers a more comprehensive analysis of data from a previous study examining the effects of selective attention on neural processing in children from different SES backgrounds (Stevens et al., 2009). The data analysis here specifically examined whether children from higher versus lower SES backgrounds differed in refractory period effects, and whether those effects interacted with the direction of selective attention. Thirty-two children (aged 3 to 8 years old) participated and were divided, based on maternal education, into a higher and lower SES group. Children were cued to attend to one of two auditory narratives presented simultaneously to the left and right ears, respectively. ERPs were recorded to 100 ms linguistic and nonlinguistic probe stimuli superimposed on both narratives, presented at ISIs of 200, 500, or 1000 ms. Previous research with this data set showed that children from lower SES backgrounds had reduced effects of selective attention on neural processing, but this earlier report did not consider the ISI between stimuli (Stevens et al., 2009). Here, we examined SES group differences in auditory processing as a function of both ISI and Attention conditions. A significant Group × ISI interaction would support the hypothesis that children from lower SES backgrounds show basic processing differences in auditory recovery cycles. In contrast, a significant Group × ISI × Attention interaction would support the hypothesis that deficits in aspects of attention serve to alter the refractory properties of the auditory system in children from lower SES backgrounds.

2. Materials and method

2.1. Participants

Thirty-two children aged three to eight years participated in the present study (range = 3.8 years to 8.7 years, $M = 6.1$ years, $SD = 1.4$, 16 girls). All participants met the following criteria for participation in the study: (1) monolingual English speakers, (2) no history of neurological or language disorders, including attention deficit hyperactivity disorder (ADHD), and (3) normal hearing, vision, and oral–motor performance on standard screenings. In addition, because our previous research indicated deficits on this task in children with Specific Language Impairment (Stevens et al., 2006, 2012), only children scoring above the 25th percentile on the receptive language composite were included in the study. This same set of 32 participants was included in an earlier paper (Stevens et al., 2009). The previous paper examined whether children in the two SES groups differed in the effects of selective attention on neural processing. In the present study, we use data from the same paradigm and participants to examine whether the SES groups differ in refractory effects, which we examine by comparing the neural response to probes presented at different inter-stimulus intervals (the previous paper did not separate the data by rate of presentation).

In order maintain a consistent coding scheme for all children in the sample, maternal education served as the exclusive measure for SES. All children in this sample currently lived with their mother and had done so since birth, but the presence and number of years of contact with fathers, step-parents, and other guardians were highly variable. While information on maternal occupation was also available, based on the Hollingshead questionnaire (Hollingshead, 1975), this information was not included in the measure of SES given the temporal instability of maternal occupational status and its lack of correlation to children's cognitive outcomes (Gottfried et al., 2003). No information was available on family income. The use of maternal education as a proxy for SES is consistent with previous research showing that maternal education alone correlates with children's cognitive outcomes (Baydar et al., 1993; Gottfried et al., 2003; Liaw and Brooks-Gunn, 1994; Noble et al., 2007; Walker et al., 1994).

Based on the criteria of maternal education as a proxy for SES, children were placed in either the “higher SES” group (defined as the mother having at least one year of college experience) or the “lower SES” group (defined as the mother having completed no more than high school). This included 16 children in each group. The majority (15) of the children in the lower maternal education had parents whose formal education ended with high school. The majority (10) of the children in the higher maternal education group had mothers who had completed partial college (at least one year), and four children had mothers with four-year degrees, and two had mothers with graduate degrees. Half of the children in each group were male, and half female. The groups also did not differ in mean age, higher SES $M = 6.0$ years, $SE = 0.4$; lower SES $M = 6.2$ years, $SE = 0.3$ years, or in receptive language standard scores of the Clinical Evaluation of Language Fundamentals (CELF; Semel et al., 1995; Wiig et al., 2004), higher SES $M = 109$, $SD = 15$; lower SES $M = 103$, $SD = 11$. Children age six years and older completed the CELF-3 (Semel et al., 1995) with receptive language scores based on the Concepts & Following Directions, Sentence Structure, and Word Classes subtests. Children younger than six years old completed the CELF-P2 (Wiig et al., 2004) with receptive language scores based on the Sentence Structure and Concepts & Following Directions subtests, along with the Word Classes subtest (for five year olds) or the Basic Concepts subtest (for children younger than five years).

All study procedures were conducted with the approval of the University of Oregon Institutional Review Board. Parents of children signed a consent form to participate. Verbal assent was obtained from the children. Families were paid for their participation.

2.2. Materials and method

Probe sounds included both a linguistic and nonlinguistic 100 ms auditory stimulus presented at 70 dB. The linguistic probe was created by digitally recording a single token of the syllable /ba/, spoken by a female, and editing the recording to 100 ms in duration. The non-linguistic probe was created by editing the /ba/ token using a scrambling procedure that rearranged 4–6 ms segments of the stimulus, resulting in a nonlinguistic 100 ms broad-spectrum ‘buzz’ that still preserved many of the acoustic properties of the linguistic probe.

The probe sounds were superimposed on digital recordings of children's stories (16 bit, 22 kHz, mean audio amplitude normalized to 60 dB SPL, A-weighted). Each story was 2.5–3.5 min. In total, eight stories were used, including four stories from the *Blue Kangaroo* series (Clark, 1998, 2000, 2002, 2003) and four stories from the *Harry the Dog* series (Zion and Graham, 1956, 1960, 1965, 1976). All stories were recorded by both a male and female narrator. (The female narrator did not generate the probe stimuli.) The digital recordings were then converted into stereo files, in which each channel (left/right speaker) presented a different children's story. The two stories presented always differed in story series (*Harry the Dog* or *Blue Kangaroo*) and narrator voice (male or female).

During the task (see Procedure and Fig. 1), children were instructed to attend selectively to one of the two audio channels, presented from separate speakers located 90° to the left and right of the child. The linguistic and nonlinguistic probe stimuli superimposed on the stories were presented at inter-stimulus intervals (ISIs) of 200, 500, or 1000 ms. The three ISIs reflected the time between successive probes, regardless of whether they occurred in the attended or unattended narrative. The narratives provided an age-appropriate task for children and permitted an experimental manipulation of selective attention embedded in the same paradigm (see Stevens et al., 2009 for results of a study comparing this same group of children based on the attention manipulation; results indicated that lower SES children have a more difficult time suppressing the neural response to probes in the unattended channel). Small, 2.5 inch images from the attended channel/story were presented on a monitor in front of the participant (57 in. away). These images were small enough to prevent eye movement contamination in the data. In addition, a small green arrow pointing to the left or the right was at the bottom of every image as a reminder of which channel to attend.

Children attended to a total of four 2.5–3.5 minute stories (two from each speaker location). Across the session, a total of 943–1007 total probe stimuli were presented, which included 78–88 probe stimuli in each of the 12 possible conditions: ISI (200/500/1000) × Probe Type (linguistic/nonlinguistic) × Attention Condition (attended/unattended). All children had at least 21 clean trials/condition for calculating averages, and most children many more (on average 52 trials/condition), available for analysis. There were no significant differences between the higher and lower SES groups in number of trials available for analysis.

2.3. Procedure

During a practice session, children were introduced to the probe stimuli and the two voices. The practice session provided instruction on paying attention to a single story while ignoring the distracting story presented in the opposite audio channel. A researcher sitting next to the child monitored behavior and asked children a series of comprehension questions following each story (described below). Caregiver(s) were able to observe the entire session remotely on a

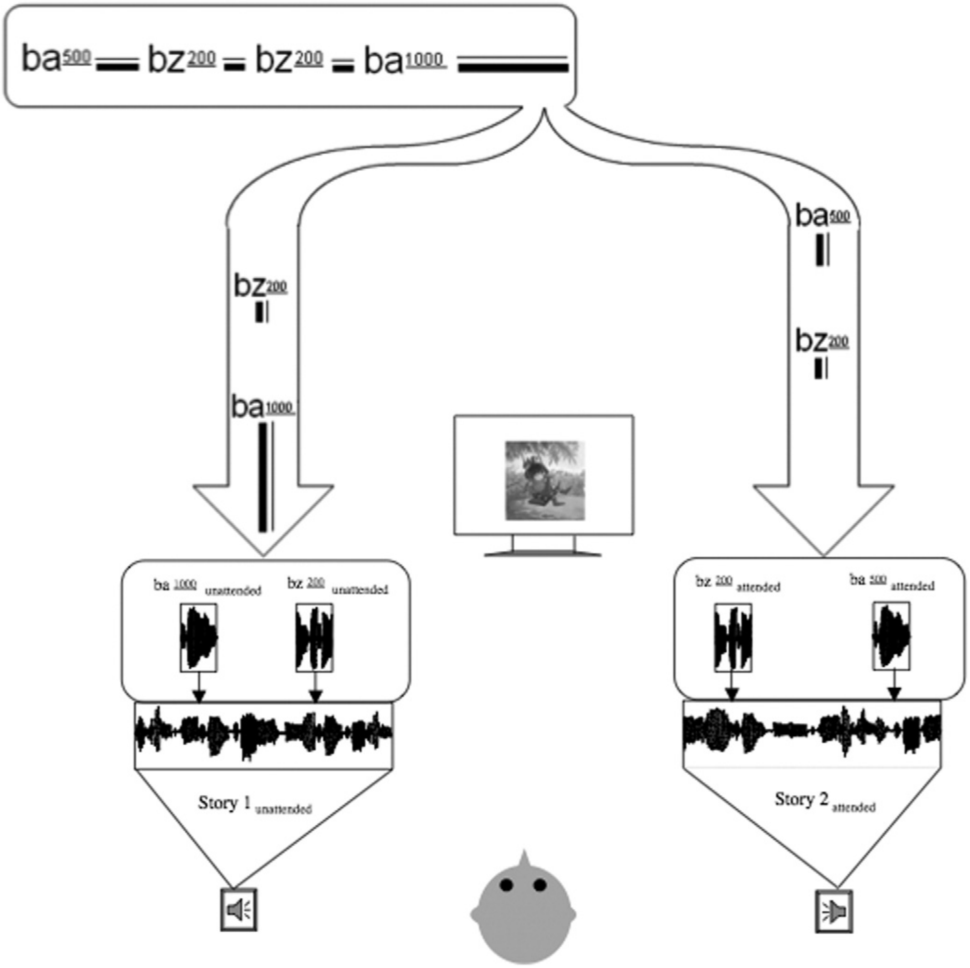

Fig. 1. Schematic representation of experimental paradigm. Children were instructed to attend to the story presented from either the left or the right speaker. ERPs were recorded to linguistic (ba) and nonlinguistic (bz) probe stimuli superimposed on both attended and ignored narratives, with the ISI between probes 200, 500, or 1000 ms.

closed circuit television showing real-time recordings from the testing booth.

Children were instructed to attend selectively to one of the two stories (left or right audio channel). Children were instructed to ignore the other story, presented simultaneously from the other audio speaker. Children attended to a total of four stories, attending twice to the story on the right side and twice to the story on the left side (order either RLLR or LRRL, counterbalanced across participants). The attended narrator and story set remained constant across the four stories for each child. After each story, the experimenter asked the child three basic, two-alternative comprehension questions about the attended story. (A response of “I don't know” was counted as an incorrect response.) At the end of all four stories, the experimenter asked one general question regarding the unattended stories. The attention questions were not designed to be a sensitive assay of children's attention abilities but instead were included to reinforce for children the goal of attending to a single story and to serve as a gross measure of children's on-task behavior. The higher and lower SES groups were matched for all stimulus factors, including attended story, start side, and narration voice.

Behavioral and ERP assessments took place across 2–3 separate days within a 30-day time window. Behavioral testing was supervised by a certified speech language pathologist and took place over one or two separate testing sessions held on different days. On a separate day, children completed the ERP testing.

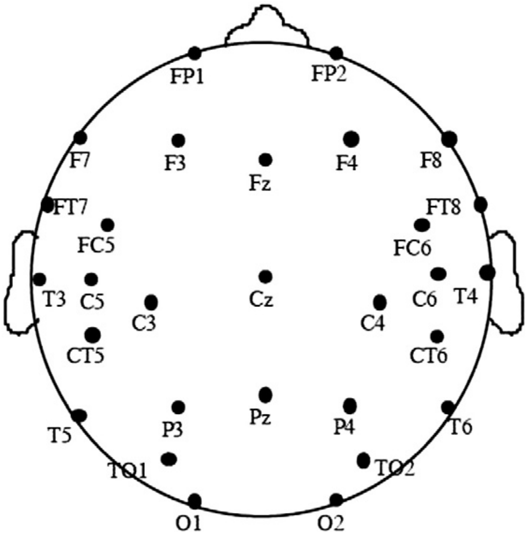

Fig. 2. Electrode configuration used in ERP recording.

2.4. Electrophysiological recording

Electroencephalogram (EEG) was recorded from 29 tin electrodes mounted in an elastic cap (Electro-Cap International, Easton, OH). Recording sites included: FP1/2, F7/8, FT7/8, F3/4, FC5/6, C3/4, C5/6, T3/4, CT5/6, P3/4, T5/6, TO1/2, O1/2, Fz, Cz, and Pz, see Fig. 2. On-line, electrodes were referenced to the right mastoid, and off-line electrodes were re-referenced to the average of the left and right mastoid. Eye movements and blinks were monitored using additional face electrodes placed at the outer canthi of each eye and beneath the right eye. The electrodes placed at the outer canthi of each eye were referenced to each other and used during artifact rejection for excessive horizontal eye movement. Electrode impedances were below 10 kΩ for eye electrodes, 5 kΩ for scalp electrodes, and 3 kΩ for mastoid electrodes. EEG was amplified 10,000 times using Grass 7P511 amplifiers (bandpass .01 to 100 Hz) and digitized online (250 Hz sampling rate). Offline, a 60 Hz digital filter was applied.

Prior to analysis, data quality was reviewed and artifact rejection performed to remove artifacts due to blinks, muscle movement, or eye movement. During artifact rejection, peak-to-peak amplitude thresholds were set, prior to normalization, for the horizontal eye channel (left and right outer canthus recording referenced to one another) as well as blinks (based on recordings at FP1 and FP2 and the electrode placed under the eye, all referenced to the linked mastoids). Muscle movement was assessed based on channel blocking. Artifact rejection was performed by individuals blind to children's socioeconomic status based on visual inspection of the raw data, and there were no significant differences between the higher and lower SES groups in final artifact rejection parameters.

Event-related brain potentials (ERPs) were averaged to the probe stimuli at the three ISIs, separately for the two probe types (linguistic/non-linguistic) and attention conditions (attended/unattended channel). ERPs were averaged for each subject at each electrode site over a 500 ms epoch, using the 50 ms pre-stimulus onset as baseline. Analyses focused on the same 16 electrodes used in our previous analysis with this data set: F7/8, F3/4, FT7/8, FC5/6, T3/4, C5/6, C3/4, and CT5/6. However, we included two factors to capture possible differences in effects as a function of electrode location: two levels of hemisphere (Right/Left) and two levels of anterior–posterior (Anterior: F7/8, F3/4, FT7/8, FC5/6; Posterior: T3/4, C5/6, C3/4, CT5/6). These electrode location factors were included in light of previous research on children with language impairment, which indicates that group differences in refractory effects can differ by hemisphere, and may be focal to anterior channels (Neville et al., 1993; Sharma et al., 2007; Stevens et al., 2012). This approach thus included relevant factors to permit a statistical test of specificity in the distribution of any effects but without constraining analysis a priori to electrode locations in studies of Specific Language Impairment. The 100–200 ms time window was selected based on visual inspection of the individual data, and with reference to our previous studies with this paradigm. We used mean amplitude measures in this time window as peak amplitude measures can be unstable (e.g., see Luck, 2005). This was particularly true for the broad positivity observed in children, which was very small or nonexistent in some children at the most rapid ISI. Consistent with the nature of the broad positivity, preliminary examination indicated that the broad positivity elicited in this paradigm did not produce stable latency measures so latency measures were not analyzed.

Mean amplitude within the 100–200 ms window for these 16 electrodes was submitted to a mixed design ANOVA. The between-subjects factor was group (Higher/Lower SES). Within-subject factors included ISI (200/500/1000), Attention (attended/unattended), Hemisphere (right/left), and Anterior–Posterior (A/P; anterior/posterior). (Preliminary analysis indicated no group differences as a function of Probe Type, so this factor was not examined.) Analyses reported below are restricted to main effects of ISI or Group, as well as interactions including ISI as a factor. Significant interactions involving Group and ISI were examined using step-down ANOVAs. To examine effects of ISI overall and within each group as indicated in the step-down ANOVAs, post-hoc repeated contrasts compared the amplitude of the response to probes at 200 versus 500 ms ISI, and then 500 and 1000 ms ISI. This procedure was used to infer where full neural recovery, within the range of ISIs tested, was observed. Full neural recovery was inferred where significant differences between successive ISIs were no longer observed. For post-hoc ISI contrasts, the sequentially rejective Bonferroni test (Holm, 1979) was used to correct for multiple comparisons. Given the two comparisons made, this set alpha for rejection at .025 for the smallest *P*-value and .05 for the next larger *P*-value. The Greenhouse–Geisser correction was applied to all tests involving factors with more than two levels, though in all cases uncorrected degrees of freedom are reported. In all cases, epsilon values for effects involving factors with more than two levels were greater than 0.8 (average epsilon = 0.92, range 0.83–0.98).

3. Results

3.1. Electrophysiological data

Fig. 3 shows the grand average ERPs to probe stimuli presented at the three ISIs, collapsed across probe type and attention condition, separately for the higher and lower SES groups. As seen in Fig. 3 grand averages, both groups of children show a single, broad positivity in response to probe stimuli, that appears to peak approximately 150 ms after stimulus onset.

The omnibus ANOVA revealed a main effect of ISI, with overall amplitude of the broad positivity larger at longer ISIs, $F(2, 60) = 21.5$, $P < .001$, partial $\eta^2 = .42$. Post-hoc repeated contrasts indicated a significant increase in the amplitude of the positivity to probes when the ISI increased from 200 to 500 ms, $F(1, 30) = 21.1$, $P < .001$, partial $\eta^2 = .41$, but no significant differences between the amplitude of the response when the ISI increased from 500 to 1000 ms, $F(1, 30) = 1.8$, $P = .19$, partial $\eta^2 = .06$. As shown in Fig. 3, across groups, the effect of ISI was somewhat more pronounced over anterior channels (ISI × A/P: $F(2, 60) = 9.1$, $P < .05$, partial $\eta^2 = .12$), but this interaction was not further examined at it was not the primary interest of the study. No other effects between ISI and the electrode location factors were significant at the .05 level, ISI × Hemisphere: $F(2, 60) = 1.2$, $P = .32$, partial $\eta^2 = .04$; ISI × Hemisphere × A/P: $F(2, 60) = 3.1$, $P = .055$, partial $\eta^2 = .09$. As well, across groups there was no significant interaction between ISI and Attention condition, either overall or as a function of electrode location, ISI × Attention: $F(2, 60) = 0.7$, $P = .49$, partial $\eta^2 = .02$; ISI × Attention × A/P: $F(2, 60) = 0.7$, $P = .50$, partial $\eta^2 = .02$; ISI × Attention × Hemi: $F(2, 60) = 0.7$, $P = .47$, partial $\eta^2 = .02$; and ISI × Attention × A/P × Hemi: $F(2, 60) = 1.2$, $P = .32$, partial $\eta^2 = .04$.

Comparing the higher and lower SES groups indicated that there was no significant main effect of Group, $F(1, 30) = 1.0$, $P = .316$, partial $\eta^2 = .03$, and the overall effect of ISI did not differ significantly between groups: Group × ISI, $F(2, 60) < 1$, $P = .98$. However, the three-way interaction between Group, ISI, and Attention condition was significant, indicating that refractory effects differed between groups as a function of attention condition, $F(2, 60) = 4.4$, $P < .02$, partial $\eta^2 = .13$. No other interactions involving Group and ISI with the electrode location factors were statistically significant (smallest $P = .23$), so subsequent analyses focused on the three-way interaction between Group, ISI, and Attention condition, using step-down analyses.

Fig. 4 presents the grand average ERPs for the three ISIs, separately for each group and attention condition at representative electrodes FC5/FC6. Grand averages for all electrodes included in analysis are presented in Supplementary Figs. 1 and 2, available online, and Table 1 presents the mean amplitudes for each group by condition, averaged over all 16 electrodes used in analysis. As shown in these figures, children from lower SES backgrounds appear to show similar

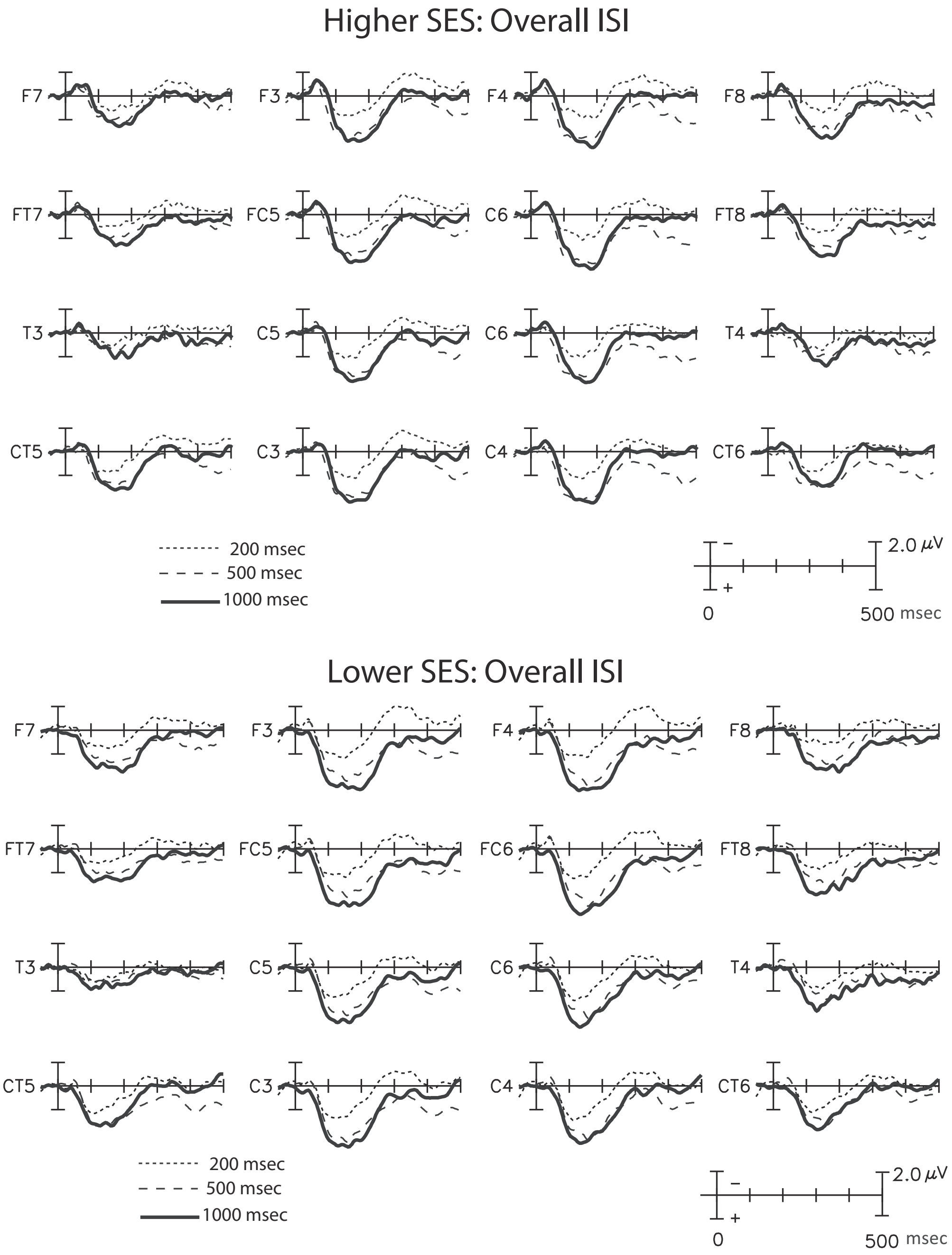

Fig. 3. Grand average ERP to the probes presented at the three ISIs (200, 500, 1000 ms), collapsed across probe type and attention condition. Upper panel shows data from higher SES group, lower panel shows data from lower SES group.

refractory effects whether probes appeared in the attended or unattended channel, with little amplitude increase in the response to probes presented at the 500 versus 1000 ms ISI in either the attended or the unattended channel. In contrast, for higher SES children, the neural recovery appears to differ in the attended and unattended conditions. In the attended condition, children from higher SES backgrounds appear to show little difference in the amplitude of the response at the 500 or 1000 ms ISI. In the unattended condition however, children from higher SES backgrounds continue to show amplitude increases in the neural response from the 500 to 1000 ms ISI, suggesting changes in the refractory period between the attended and unattended conditions.

To explore the nature of the interaction statistically, step-down analyses were conducted. First, separate ANOVAs were conducted for the higher and lower SES groups to determine if there was a significant effect of ISI in both attend and unattend conditions. These ANOVAs included factors of ISI (200, 500, 1000) and Attention condition (Attend, Unattend). Probe type, Hemisphere, and Anterior/Posterior factors were also included in the analysis, as these factors explained overall variance in the ERPs, but effects involving these factors are not included in the stepdown results, as they did not differ by Group in the omnibus analysis. Second, additional analyses compared the nature of refractory effects in each group, using repeated contrasts to compare the 200 and 500 ms ISI, and the 500 and 1000 ms ISI. These contrasts were used to isolate the ISI at which continued amplitude increases were no longer observed. Table 2 presents the results of this step-down analysis, described below.

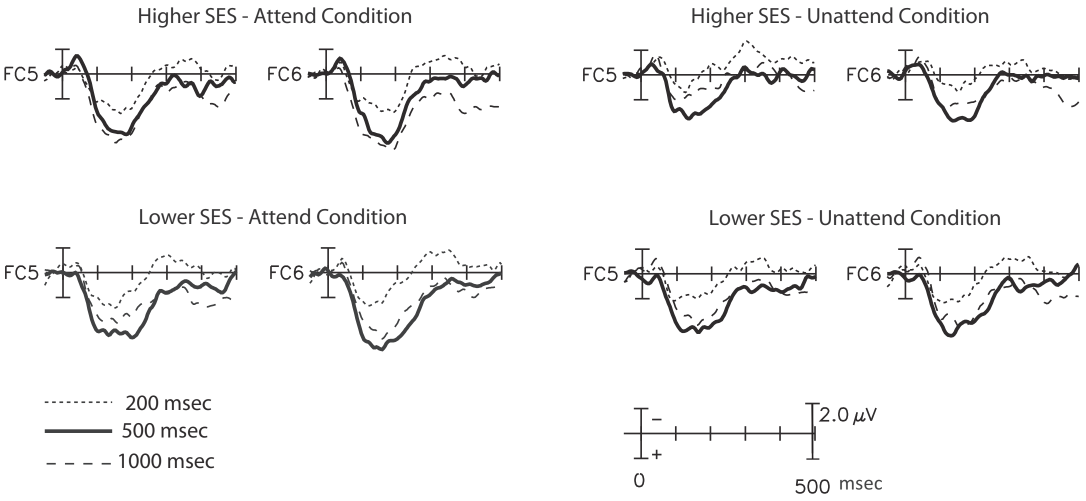

Fig. 4. Grand average ERPs from representative electrodes FC5/6 to the probes presented at the three ISIs (200, 500, 1000 ms), separately for the attended and unattended conditions. Top row shows data from higher SES group, lower row shows data from the lower SES group. Grand averages showing all electrodes available as supplementary figures online.

The step-down analysis indicated that children from lower SES backgrounds showed a significant overall effect of ISI, $F\,(2, 30) = 8.03$, $P < .01$, partial $\eta^2 = .35$, but this effect did not differ as a function of Attention condition, ISI × Attention, $F\,(2, 30) = 1.0$, $P = .36$, partial $\eta^2 = .17$. Repeated comparison contrasts corrected for multiple comparisons indicated that in the lower SES group, the response to probes at the shortest 200 ms ISI was reduced compared to the response to probes at the 500 ms ISI, $F\,(1, 15) = 7.8$, $P = .014$, partial $\eta^2 = .34$, but there was no difference in the amplitude of the neural response to probes at 500 versus 1000 ms ISI, $F\,(1, 15) = 1.1$, $P = .31$, partial $\eta^2 = .07$. In other words, children in the lower SES group showed no continued significant increase in the neural response as the ISI increased from 500 ms to 1000 ms, whether probes were in the attended or unattended channel.

In contrast, step-down analysis restricted to children from higher SES backgrounds indicated both a main effect of ISI, $F\,(2, 30) = 16.2$, $P < .001$, partial $\eta^2 = .52$, as well as a significant interaction between ISI and Attention condition, $F\,(2, 30) = 3.56$, $P < .05$, partial $\eta^2 = .19$. Thus, in the higher SES group only, refractory effects differed as a function of whether probes were presented in the attended or unattended channel. In the Attend condition, higher SES children showed a significant overall effect of ISI, $F\,(2, 30) = 8.3$, $P < .01$, partial $\eta^2 = .36$. Repeated comparison contrasts corrected for multiple comparisons indicated the response to probes at the shortest 200 ms ISI was significantly reduced compared to the response to probes at the 500 ms ISI, $F\,(1, 15) = 23.6$, $P < .001$, partial $\eta^2 = .61$, but there was no significant difference in the amplitude of the neural response to probes at 500 versus 1000 ms ISI, $F\,(1, 15) = 2.3$, $P = .15$, partial $\eta^2 = .13$. In other words, in the Attend condition, higher SES children showed no significant increase in the amplitude of the neural response as the ISI increased from 500 to 1000 ms. In the Unattend condition, higher SES children also showed a significant overall effect of ISI, $F\,(2, 30) = 9.1$, $P = .001$, partial $\eta^2 = .38$. However, in the Unattend condition, repeated comparison contrasts corrected for multiple comparisons indicated a trend for a larger neural response at each increasing ISI: 200 vs 500 ms ISI, $F\,(1, 15) = 3.2$, $P = .09$, partial $\eta^2 = .18$; 500 versus 1000 ms ISI, $F\,(1, 15) = 6.1$, $P = .026$, partial $\eta^2 = .29$, indicating that when stimuli are not attended, at least a full second is required for complete neural recovery in the higher SES group. Thus, in the higher SES group only, stimuli in the Unattended channel showed a longer recovery time, requiring at least a full second ISI to show full amplitude response. In all other groups and conditions, no continued significant increase in the neural response was observed as the ISI increased from 500 to 1000 ms.

Another way to characterize the nature of the three-way interaction between Group, ISI, and Attention is to directly compare the neural response in higher and lower SES groups at each of the three ISIs, separately in the attend and unattend conditions. Using the sequentially rejective Bonferroni correction for multiple comparisons (Holm, 1979), corrected alpha levels for the three tests in each attention condition were set at .017 for the smallest P-value (.05/3), .025 for the second smallest P-value (.05/2), and .05 for the next larger P-value (.05/1). Table 1 presents the mean amplitude response for each group in these conditions. In this supplemental analysis, group differences were observed only at the two shorter ISIs in the Unattend condition. Specifically, corrected for multiple comparisons, in the Unattend condition, the lower SES group showed a larger neural response relative to the higher SES group at the 500 ms ISI: $t\,(30) = 2.64$, $P = .013$, $d = +.93$ and also tended to show a larger neural response at the 200 ms ISI: $t\,(30) = 2.17$, $P = .038$, $d = +.76$. In contrast, no significant differences were observed between groups in the Unattend condition at 1000 ms ISI: $t\,(30) = 0.13$, $P = .894$, $d = +.05$, or in the Attend condition at the 200, 500 or 1000 ms ISI: $t\,(30) = -.88$, $P = .385$, $d = -.31$; $t\,(30) = -1.53$, $P = .135$, $d = -.53$; $t\,(30) = 1.12$, $P = .271$, $d = .40$, respectively. This suggests that children from lower SES backgrounds are less able to suppress unattended stimuli, but only when stimuli are

Table 1
Mean amplitude from 100 to 200 ms (in μV) as a function of ISI and attention conditions, separately for the higher and lower SES groups. Standard error in parentheses.

Group	Attend condition			Unattend condition		
	200 ISI	500 ISI	1000 ISI	200 ISI	500 ISI	1000 ISI
Higher SES	2.3 (0.30)	4.3 (0.75)	3.5 (0.42)	0.4 (0.35)	1.5 (0.42)	2.9 (0.42)
Lower SES	1.9 (0.38)	3.3 (0.48)	4.1 (0.35)	1.5 (0.38)	3.0 (0.40)	3.0 (0.45)

Table 2
Summary of significant interactions and step-down analyses for comparison of the neural response to probe stimuli in higher and lower SES children. Only effects relevant to the step-down analysis of three-way interaction are reported.

Source	*df*	*F*	*P*
Omnibus			
G × ISI × A	2, 60	4.4	.017
Within lower SES group			
ISI	2, 30	8.0	.003
ISI × A	2, 30	1.0	.366
Within higher SES group			
ISI	2, 30	16.2	<.001
ISI × A	2, 30	3.6	.047
Higher SES only, ISI effects by attention condition			
ISI, attend condition	2, 30	8.3	.002
ISI, unattend condition	2, 30	9.1	.001

Note: G = group; ISI = interstimulus interval; A = attention condition.

presented rapidly (e.g., those with ISIs of 200 or 500 ms), resulting in the faster neural recovery observed in the Unattend condition for the lower SES group relative to the higher SES group.

3.2. Comprehension questions

In response to comprehension questions about the attended story, all children answered at least half of the questions correctly, indicating the children were willing and able to complete the task. There were no significant differences between the higher and lower maternal education groups in the number of comprehension questions correctly answered about the attended stories, $t\ (30) = -.17$, $P = .87$, higher maternal education $M = 10.1$, $SE = 0.28$, lower maternal education $M = 10.2$, $SE = 0.23$. Responses to the single question about the unattended story were at chance levels for both groups, largest one-sample $t = 1.6$, $P = .14$, and also did not differ between groups, Fisher's Exact $P = 1.0$.

4. Discussion

The present study suggests that several aspects of basic auditory processing are similar in children from higher and lower SES backgrounds. Across groups, the basic morphology of auditory evoked response was qualitatively similar, evident as a broad positivity from approximately 100–300 ms post-stimulus onset. Moreover, collapsed across attention condition, no evidence was found for overall group differences in auditory refractory effects. In addition, no support was found for more focal group differences in auditory refractory effects as a function of electrode location factors. Thus, children from lower SES backgrounds did not exhibit overall differences in auditory refractory effects in contrast to those previously reported in children with Specific Language Impairment (Neville et al., 1993; Stevens et al., 2012).

While overall auditory refractory effects were similar in children from higher and lower SES groups, differences in refractory effects did emerge as a function of attention condition. We and others have previously reported that children from lower SES backgrounds show significantly reduced effects of selective attention on neural processing (D'Angiulli et al., 2008; Stevens et al., 2009). Here, when the ISI between probe stimuli was included as a factor in a selective attention paradigm, we found a significant three-way interaction between group, attention condition, and ISI. Children from lower SES backgrounds showed similar refractory period effects regardless of the direction of selective attention, with no significant difference in the amplitude of the neural response for stimuli presented with 500 versus 1000 ms between successive stimuli, suggesting full neural by 500 ms regardless of the direction of selective attention. In contrast, children from higher SES backgrounds showed no significant difference in the amplitude of the neural response for stimuli presented at interstimulus intervals of 500 versus 1000 ms, but only if stimuli were presented in the attended channel. For children from higher SES backgrounds, when stimuli were presented in the unattended channel, auditory refractory effects were still evident, but the auditory system required more time – at least 1000 ms – to show full neural recovery. Framed another way, for children from higher SES backgrounds, the attenuation of unattended stimuli is greatest for stimuli presented at more rapid rates (200 or 500 ms ISI), resulting in alterations in basic auditory recovery period effects. While the children from higher SES backgrounds show a clear refractory effect in both attended and unattended conditions, the recovery occurs more quickly in the attended condition (full amplitude apparent with an ISI of 500 ms, indicated by no detectable differences in the amplitude of the response for ISIs of 500 and 1000 ms) and takes longer in the unattended condition (requiring at least an ISI of 1000 ms).

These data suggest that top down modulation of auditory processing interacts in important ways with stimulus-driven properties, including rate of presentation. For children from higher SES backgrounds, selective attention is particularly effective at suppressing the neural response to *rapidly* presented auditory information. When examined in the framework of auditory recovery cycles, the result is a longer recovery cycle when stimuli are presented in an unattended channel. The functional consequence of this interaction might be reducing the responsiveness to irrelevant auditory stimuli, particularly when those stimuli are presented rapidly and repetitively. At the same time, it may be advantageous to set an attentional filter that remains responsive to less frequently presented stimuli, i.e., those occurring after a longer gap in auditory stimulation, as a way of detecting potentially relevant changes in the environment. However, this same interaction between attention and rate of presentation was not observed in children from lower SES backgrounds. This suggests that for children from lower SES backgrounds, not only is unattended information less effectively suppressed than in children from higher SES backgrounds, but this group difference also is particularly pronounced when stimuli are presented at rapid rates. Indeed, direct between-group comparisons indicated that group differences were specific to an increased amplitude response to unattended probes (i.e., poorer attentional filtering) in the lower SES group, but only at the two shorter ISIs.

The present study indicates that, at least in higher SES children, selective attention alters the neural response in a way that is also dependent on the rate of stimulus presentation. In contrast, our previous study comparing children with SLI and typically developing children using a similar paradigm did not find an interaction between attention condition and ISI (Stevens et al., 2012). The differences with the present study could be attributed to the lower overall SES and younger age of participants in the previous study, or subtle differences in the paradigms used. Indeed, in a study of adults, Woldorff and Hillyard (1991) observed interactions between selective attention and rate of stimulus presentation similar to those reported here. In their study, Woldorff and Hillyard compared ERPs to auditory stimuli at relatively rapid rates of presentation ('shorter' ISIs of 120–220 ms versus 'longer' ISIs of 220–320 ms) while also manipulating the direction of selective attention. Results indicated that later phases of the early attentional negativity (104–154 ms) showed the largest attention effects at the shorter ISIs when stimuli were also presented in the same ear, suggesting, similar to the present study, that selective attention may be recruited particularly strongly when auditory refractory effects would be expected to be strongest (i.e., the same stimulus is presented from the same location, at a very rapid ISI). However, the interactions between selective attention and stimulus properties are likely more complex, as the same study also reported an *opposite* effect of ISI during an earlier phase of the attentional negativity (60–100 ms). Thus, it will be important for future research to examine the complex ways in which top-down attentional control and stimulus-driven properties interact across development to influence basic auditory processing.

One limitation in the present study was the restricted range of maternal education levels represented in the data set. As few children in the study had mothers with extreme education levels (less than a high school degree on the lower end or more than a four-year degree on the higher end), we chose to binarize maternal education rather than treating it as a continuous variable. However, a stronger test of SES-related differences in auditory processing would include participants with a greater range of SES backgrounds. Indeed, the actual difference in maternal education groups was relatively small (only a few years of education). Thus, it is possible that our study has underestimated differences in auditory processing due to SES. However, it is also possible that a cut point involving even partial college represents a meaningful difference in parent education levels. We do not know, for example, whether mothers with partial college continued their education beyond the study. Instead, our measure of maternal education captures only educational attainment at one moment in time. Related to the measurement of SES, we did not have access to data on family income, which is one component of many SES measures. While maternal education is often used as a proxy for SES and is recognized as a strong of childhood outcomes (Baydar et al., 1993; Gottfried et al., 2003; Liaw and Brooks-Gunn, 1994; Noble et al., 2007; Walker et al., 1994), it would have been preferable to have income data available. In addition, although we screened children for the presence of any current language or neurological disorders (e.g., attention deficit hyperactivity disorder, language impairment), the children in this study were relatively young. We did not track children longitudinally or collect family history data, and therefore do not know if any children were later diagnosed with developmental disorders that may not manifest until later ages (e.g., dyslexia). Finally, while we inferred full neural recovery when significant differences between successive ISIs were no longer observed, it is of course impossible to statistically demonstrate no differences. Thus, it is possible that small but non-significant differences do continue to occur from 500 to 1000 ms ISIs in some conditions, and also that continued amplitude recovery might have been observed had ISIs beyond 1000 ms been included. However, the significant between-group differences provide strong support that refractory effects differ as a function of attention condition among children from higher versus lower SES backgrounds.

The present findings have implications for larger efforts to identify the cognitive skills and neural systems underlying SES-related disparities. Previous research has identified aspects of attention and language as particularly vulnerable in children from lower SES backgrounds (Hackman and Farah, 2008; Hackman et al., 2010; Mezzacappa, 2004; Noble et al., 2005; Stevens et al., 2009). Here, we found that group differences in selective attention interacted with rate of stimulus presentation, but no group differences were observed in overall refractory cycle effects. This suggests that, unlike children with Specific Language Impairment, who sometimes demonstrate overall differences in low-level auditory refractory period effects (Neville et al., 1993; Stevens et al., 2012), children from lower SES backgrounds show differences in auditory refractory periods only when stimuli are presented in an unattended channel. Thus, the present data are consistent with models positing cascading consequences of selective attention for processing. The data are also consistent with models emphasizing the role of linguistic input for supporting language development in children from lower SES backgrounds (Hart and Risley, 1995; Hoff, 2003; Hurtado et al., 2008; Huttenlocher et al., 2002). Thus, selective attention and linguistic input may represent more meaningful targets for interventions designed to reduce SES-related achievement gaps. Indeed, it will be important for future research to continue identifying the cognitive skills and neural systems that underlie SES-related academic disparities, as well as the mechanisms that give rise to these differences. Such research holds the promise of identifying the most relevant targets and intervention approaches that will be useful in reducing the SES achievement gap.

5. Conclusion

The present study indicates that whereas overall refractory cycle effects are similar in children from higher and lower SES groups, differences in recovery cycle effects can emerge as a function of attention condition. These findings are consistent with models positing cascading consequences of selective attention in children from lower SES backgrounds.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ijpsycho.2014.06.017.

Acknowledgments

This research was supported by NIH/NIDCD grant DC00481 to HJN and a Science Collaborative Research Program (SCRP) grant from Willamette University to CS. We are grateful to the members of the child testing team at the Brain Development Laboratory at the University of Oregon involved in collecting the behavioral and ERP data.

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