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Research Report

Neurophysiological evidence for selective auditory attention deficits in children with specific language impairment

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ABSTRACT

Recent behavioral studies suggest that children with poor language abilities have difficulty with attentional filtering, or noise exclusion. However, as behavioral performance represents the summed activity of multiple stages of processing, the temporal locus of the filtering deficit remains unclear. Here, we used an event-related potential (ERP) paradigm to compare the earliest mechanisms of selective auditory attention in 12 children with specific language impairment (SLI) and 12 matched control children. Participants were cued to attend selectively to one of two simultaneously presented narrative stories. The stories differed in location (left/right speaker), narration voice (male/female), and content. ERPs were recorded to linguistic and nonlinguistic probe stimuli embedded in the attended and unattended story. By 100 ms, typically developing children showed an amplification of the sensorineural response to attended as compared to unattended stimuli. In contrast, children with SLI showed no evidence of sensorineural modulation with attention, despite behavioral performance indicating that they were performing the task as directed. These data are the first to show that SLI children have marked and specific deficits in the neural mechanisms of attention and, further, localize the timing of the attentional deficit to the earliest stages of sensory processing. Deficits in the effects of selective attention on early sensorineural processing may give rise to the diverse set of sensory and linguistic impairments in SLI children.

1. Introduction

An estimated 7% of school aged children experience deficits in oral language ability that cannot be explained by age, general intelligence, or educational opportunity (Tomblin et al., 1997). Among children with this profile of specific language impairment (SLI), 50% will go on to experience reading difficulties and develop dyslexia (Bishop and Snowling, 2004; Catts, 1993; Eisenmajer et al., 2005; McArthur and Hogben, 2001). Although linguistic deficits fundamentally characterize both SLI and dyslexia (Bishop and Snowling, 2004; Snowling, 2001; Stanovich, 1988), at least some individuals with language disorders have concomitant deficits in nonlinguistic perceptual tasks including motion perception (Demb et al., 1998; Stevens and Neville, 2006; Talcott et al., 2002) and rapid auditory processing (Farmer and Klein, 1995; Klein and Farmer, 1995; Tallal, 1980; Tallal et al., 1998).

Event-related brain potentials (ERPs) have helped to characterize the neurobiological underpinnings of the sensory, cognitive, and linguistic deficits observed in SLI. For

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example, a number of studies indicate reduced amplitude, delayed latencies, or otherwise abnormal cortical evoked responses to visual and auditory stimuli in SLI (Bishop and McArthur, 2004; McArthur and Bishop, 2004, 2005; Neville et al., 1993). These differences have been observed for both short and long duration stimuli at relatively rapid and slow presentation rates, indicating that the deficit is not specific to rapid auditory or visual processing. SLI has also been associated with reduced or absent mismatch negativity responses to speech stimuli, suggesting deficits in sensory memory or automatic comparison processes (Shafer et al., 2005; Uwer et al., 2002). During sentence processing, children with SLI show more bilateral (less specialized) responses to closed class words, and larger N400 responses to open class words (Neville et al., 1993). Taken together, these ERP studies suggest that the behavioral manifestations of SLI may arise from differences in early aspects of sensory processing.

However, the ERP literature on language disorders is also characterized by inconsistencies across studies (for a discussion, see McArthur and Bishop, 2004; Neville et al., 1993; Uwer et al., 2002). Such inconsistencies could reflect the heterogeneous nature of SLI, which can arise from or manifest as different profiles of deficits in different children (Neville et al., 1993). Under this framework, a specific deficit is neither necessary nor sufficient to produce SLI (Bishop et al., 1999), but instead, as in medical models of heart disease or lung cancer, SLI arises from the complex interplay of several risk and protective factors acting in concert. Evidence for the heterogeneity of SLI is clear within individual studies. For example, some ERP differences are observed only among SLI individuals scoring low on related behavioral tests (Neville et al., 1993), or of a younger chronological age (Bishop and McArthur, 2004; McArthur and Bishop, 2005). Differences across studies might also be accounted for by stimulus complexity, with SLI deficits emerging primarily when performance requires selecting a critical feature from among co-present, but task-irrelevant, information (e.g., McArthur and Bishop, 2005 show SLI deficits when discriminating complex spectral tones, in which changes are identified by differences in only one of four formants). This latter suggestion raises the possibility that differences in attentional processes, and specifically attentional filtering, may be compromised in SLI. Indeed, the need to assess attention explicitly in SLI has emerged as a consistent theme in the literature (Bishop et al., 1999; Neville et al., 1993; Rosen, 2003; Uwer et al., 2002).

A number of recent behavioral studies have reported deficits in attentional filtering, or noise exclusion (Asbjørnsen and Bryden, 1998; Atkinson, 1991; Cherry, 1981; Sperling et al., 2005; Ziegler et al., 2005) and other aspects of attention (Facoetti et al., 2003; Hari and Renvall, 2001; Schul et al., 2004; Thomson et al., 2005; Visser et al., 2004) among individuals with dyslexia or SLI. The observed attentional filtering deficits span both linguistic and nonlinguistic domains within the auditory and visual modalities (Asbjørnsen and Bryden, 1998; Atkinson, 1991; Cherry, 1981; Sperling et al., 2005; Ziegler et al., 2005). However, as behavioral performance represents the summed activity of multiple stages of processing (e.g., perception, response selection), the temporal locus of the filtering deficit remains unclear.

To date, no research has examined the neurobiology of filtering, or selective attention, among individuals with language disorders. The most relevant study (Shafer et al., 2005) compared auditory evoked responses to vowel stimuli under a passive listening condition (participants watched a movie and were instructed to ignore the sounds) and an active attend condition (participants detected an auditory tone amidst the vowel sounds). Although the focus of the study was the mismatch negativity to occasional deviant vowel sounds, the paper also compared ERPs to the standard stimuli in the two conditions. Compared to the passive condition, in the active attend condition children showed a smaller P100 (negative processing difference) and a smaller N200–250 (positive processing difference). While both typically developing and SLI children showed modulation of the P100, only typically developing children showed modulation of the N200–250. While it is tempting to conclude from these data that the earliest effects of attention are intact in SLI whereas later processes might be compromised, the design of the study actually manipulated arousal (task versus no task) rather than the process of selectively attending to a subset of competing stimuli. A second study (Harter et al., 1989) examined the effects of endogenous, spatial cuing on visual evoked potentials to target squares in dyslexic and typical readers. Although group differences were apparent in the study, several methodological limitations obscure interpretation of the data, including co-presence of exogenous orienting cues on all trials, lack of clear ERP components, especially in the typically developing children (see Fig. 1 in Harter et al., 1989), and high rates of participant exclusion (approximately 50% of the sample). Further, some group differences did not hold after partialing out the effects of nonverbal IQ and age. Thus, while behavioral studies present clear evidence for filtering deficits in children with language disorders, the neurobiological mechanisms underlying this deficit are not yet understood. However, there is a rich history of ERP studies on selective auditory attention in adults, and recent studies in typically developing children, that provide methodological traction for exploring the nature of selective attention deficits in SLI.

Event-related brain potentials (ERPs) have been powerful in illuminating when, how, and where selective auditory attention operates in adults (Hillyard et al., 1973; Hillyard et al., 1987; Woldoff and Hillyard, 1991). In a standard experimental procedure, separate streams of auditory stimuli are presented to the right and left ears. Participants monitor one of the two streams for rare, deviant stimuli. ERPs are compared to standard stimuli when attended and unattended. In adults, the amplitude of ERP components to attended as compared to unattended standard stimuli are enhanced by 100 ms, suggesting attentional modulation of early sensory processing.

We recently developed a child-friendly version of this ERP paradigm (Coch et al., 2005; Sanders et al., 2006). Participants attend to one of two children's narratives, and ERPs are recorded to probe stimuli superimposed on the attended and unattended story (see Fig. 1). Using this paradigm, we have studied the nature and timing of selective auditory attention in adults and typically developing (TD) children as young as 3 years (Coch et al., 2005; Sanders et al., 2006). While adult

ERPs to probe stimuli show a clear P1 and N1 component, children's ERPs show a single, broad positivity from 100 to 300 ms. This difference in morphology is consistent with developmental work showing that children's auditory evoked potentials are dominated by a broad, positive response followed by a later negativity (Ponton et al., 2000; Sharma et al., 1997). However, despite differences between the ERP morphology in children and adults, both groups show a larger response to attended stimuli by 100 ms. For adults, the attentional modulation resembles a classic enhanced negativity on the N1 (a negative processing difference). In contrast, children show an enhanced broad positivity at 100 ms (a positive processing difference). This suggests that even young children show "on-time" attentional modulation of early sensory processing.

Here, we used the same ERP paradigm to compare the early mechanisms of selective auditory attention in 12 children with SLI and 12 matched control TD children. We tested the hypothesis that children with SLI would show reduced or absent neural differentiation of attended and unattended auditory information during the early stages of sensory processing that are typically modulated by selective attention.

2. Results

2.1. Demographic variables

As expected based on selection criteria, the SLI and TD groups differed significantly in CELF receptive language, expressive language, and total language scores, all $t_{16}>4$, $P<0.001$, as shown in Table 1. On average, the SLI group scored in the 6th percentile for receptive language, and the TD group in the 57th percentile. Children with SLI had an average discrepancy of 1.5 standard deviations (22 standard scores) between their receptive language and nonverbal IQ. Aside from these group differences in language ability, the SLI and TD children did not differ in age, gender, or nonverbal IQ. The groups also did not differ in socio-economic status (SES), either as measured using the Hollingshead 4-Factor Index (Hollingshead, 1975), or a measure of maternal education.

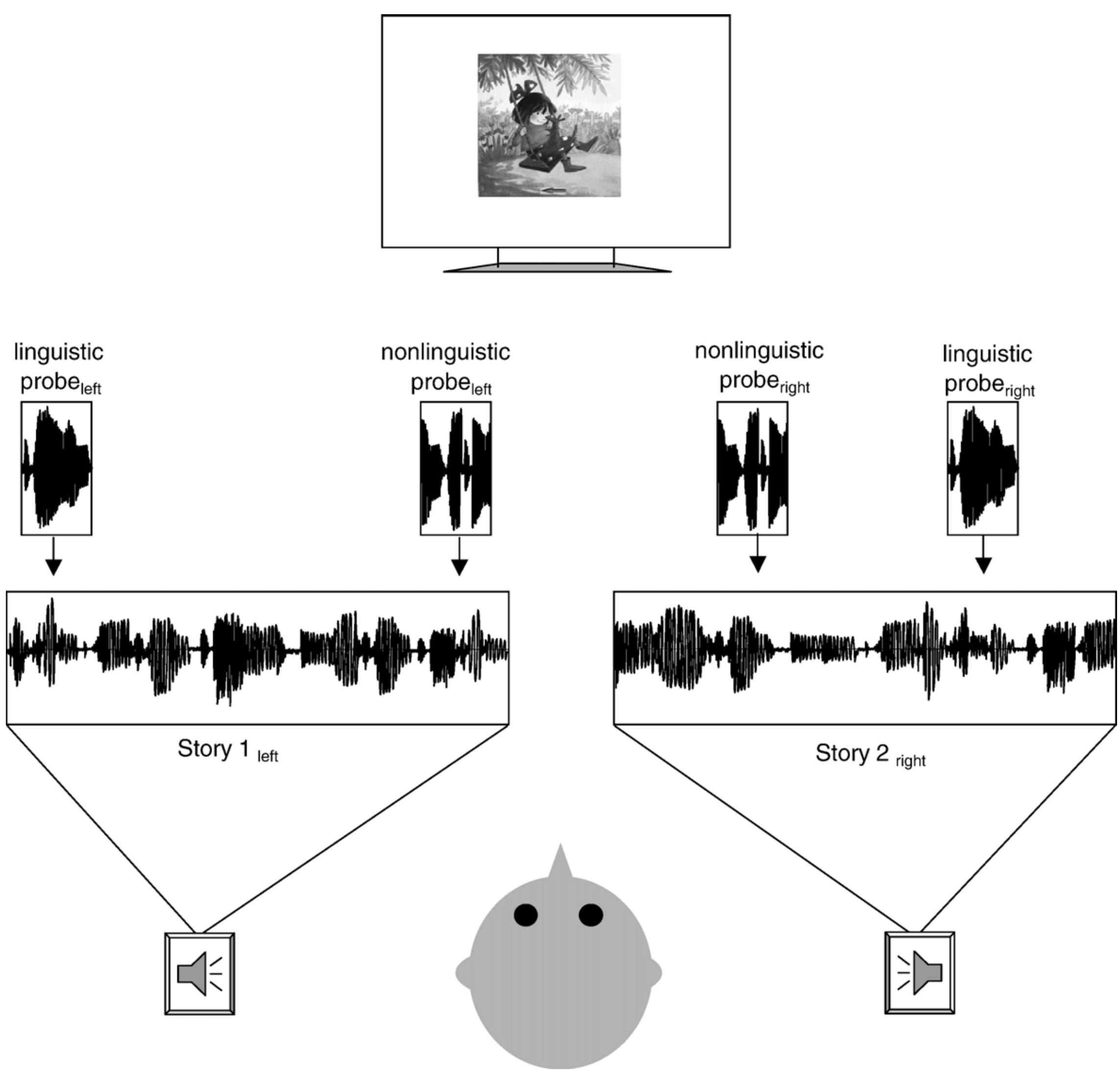

Fig. 1 – Selective auditory attention experimental paradigm.

Table 1 – Demographic and behavioral characteristics of specifically language impaired (SLI) and typically developing (TD) groups

	TD $n=12$	SLI $n=12$	P
Age	6.0 (1.4)	5.6 (1.5)	.38
Gender	5 M, 7 F	6 M, 6 F	.99
Handedness	12 R, 0 L	11 R, 1 L	.99
Socio-economic status [a]	34 (9)	39 (14)	.37
Maternal education [b]	4.8 (.4)	5.2 (.9)	.22
Stanford–Binet 5 non-verbal IQ, standard scores			
Non-verbal IQ	99.6 (6)	96.4 (9)	.31
Clinical evaluation of language fundamentals, standard scores			
Receptive language	103.2 (10)	73.0 (7)	<0.001
	57th %ile	6th %ile	
Expressive language	100.8 (8)	78.8 (14)	<0.001
	52nd %ile	18th %ile	
Total language	103.0 (8)	75.2 (12)	<0.001
	57th %ile	8th %ile	

Standard deviations are in parentheses.
[a] Socio-economic status (SES) estimated using the Hollingshead 4-factor index of social position. Values range from 8 to 66. Higher scores represent higher SES. Scores of 30–39 represent middle class.
[b] Maternal education coded using the Hollingshead scoring code. Values range from 1 to 7. Higher scores represent higher levels of attained education. Score of 5 represents partial college or specialized training.

2.2. Electrophysiological data

Separate event-related potentials (ERPs) to the four types of probe stimuli (attended/unattended × linguistic/nonlinguistic) 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. Following artifact rejection, there were no differences between groups in the number of ERP trials available for analysis in any bin, which is an indirect measure of motor and eye movements, largest $t(22)=1.1$, $p=0.3$. All children had at least 49 trials, and on average 162 trials, available for analysis in each of the four bins.

2.2.1. Group differences in the attention effect

ERP data were analyzed using a 2×2×2 mixed design ANOVA on the mean amplitude of the ERP from 100 to 200 ms post-stimulus onset, averaged over the anterior four rows of 16 electrodes (F7/8, FT7/8, F3/4, FC5/6, C3/4, C5/6, CT5/6, T3/4). This set of electrodes was selected based on both past research using the auditory attention paradigm (Coch et al., 2005; Sanders et al., 2006) and the distribution of the attention effect apparent in the current data from TD children. The 100–200 ms time window was selected because, in our ongoing analyses with typically developing children (Sanders et al., 2006), we find a reliable effect of attention for children age 3–5 and 6–8 years during this early time window, although younger children continue to show an effect from 200 to 300 ms. Within-subject factors included attention (attended/unattended) and probe type (linguistic/nonlinguistic). The between-subject factor was group (SLI/TD).

In response to probe stimuli, both SLI and TD children showed a single, broad positivity peaking around 150 ms post-stimulus onset (see Figs. 2a, b). The main effect of group was not significant, $F(1,22)=1.5$, $p>0.2$, nor was the interaction between group and probe type, $F(1,22)<1$, $P>0.8$. Across groups, the positivity was larger to probes in the attended

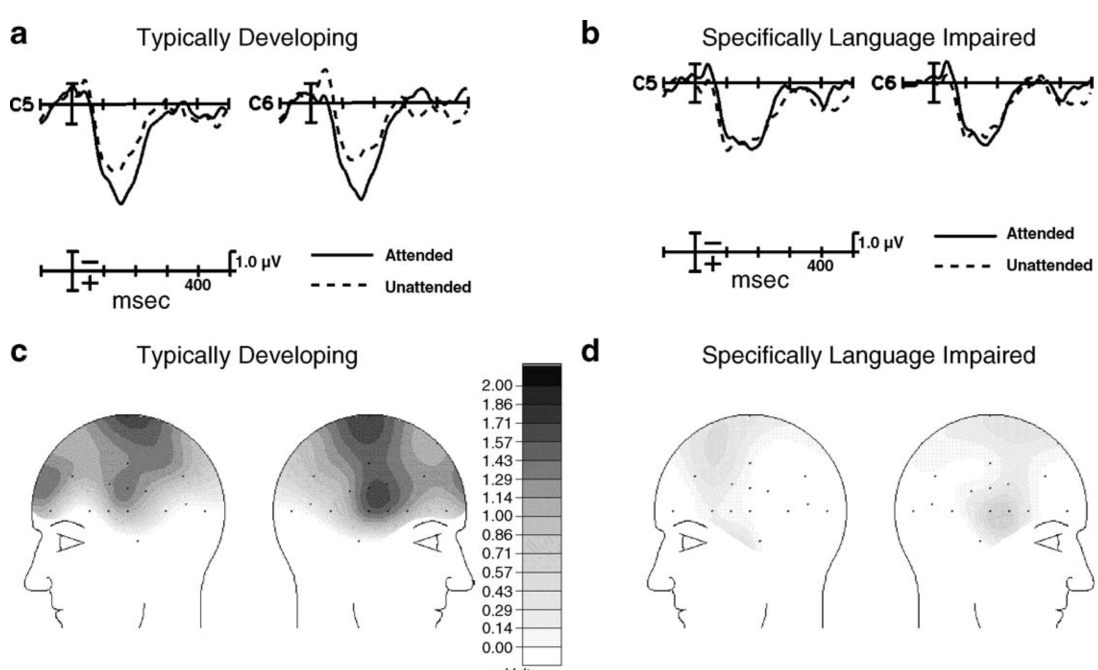

Fig. 2 – Grand average evoked potentials for attended and unattended stimuli, collapsed across linguistic and nonlinguistic probes, (a) in the TD group ($P=0.001$) and (b) in the SLI group ($P>0.4$). Voltage map of the attention effect (Attended–Unattended) shows (c) in TD children a broadly distributed effect and (d) in SLI children no modulation with attention.

compared to the unattended channel, main effect of attention, $F(1,22) = 16.8$, $P < 0.001$.

Crucial to the hypothesis of the study, the group × attention interaction was significant, $F(1,22) = 6.4$, $P < 0.005$, indicating that the effect of attention differed for the SLI and TD children (see Figs. 2a–d). As the group difference in attention did not differ by probe type (group × attention × probe type, $F(1,22) = 1.2$, $P = 0.28$), simple effects tests for the difference between attended and unattended stimuli were computed for each group, collapsed across probe type. Consistent with past research, TD children showed a larger positivity to probes in the attended ($M = 3.8$ μV, $SE = 0.4$ μV) versus unattended ($M = 2.5$ μV, $SE = 0.5$ μV) channel, paired-samples $t(11) = 4.3$, $P = 0.001$. In marked contrast, children with SLI showed no evidence of attentional modulation during this time window, paired samples $t(11) < 1$, $P > 0.4$, attended $M = 2.6$ μV, $SE = 0.1$ μV and unattended $M = 2.5$ μV, $SE = 0.2$ μV. Analyses conducted over electrodes C5 and C6, shown in Fig. 2, produced the same pattern of results: group, $P > 0.2$; group × attention, $P < 005$; simple effects tests of the effect of attention in the TD group, $P = 0.001$, and in the LI group, $P > 0.7$.

Attentional modulation involves two processes: enhancement of attended stimuli and suppression of distracting, competing stimuli. If the magnitude of the evoked response to attended and unattended stimuli is taken as an index of each of these processes, respectively, direct comparison of the two groups could identify whether the SLI deficits are associated with abnormalities in one or both attentional mechanisms. Whereas the two groups did not differ in response to unattended probe stimuli, independent samples $t(22) < 1$, $P > 0.9$, the SLI group showed a smaller response to attended stimuli, independent samples $t(22) = 2.3$, $P < 0.03$, see Fig. 3. This suggests that the SLI deficit in selective attention was associated specifically with deficits in signal enhancement, as opposed to distractor suppression. Analyses conducted over electrodes C5 and C6 showed the same pattern of results. Whereas the two groups did not differ in response to unattended probes ($P > 0.9$), the SLI group showed a smaller response to attended stimuli ($P < 0.04$).

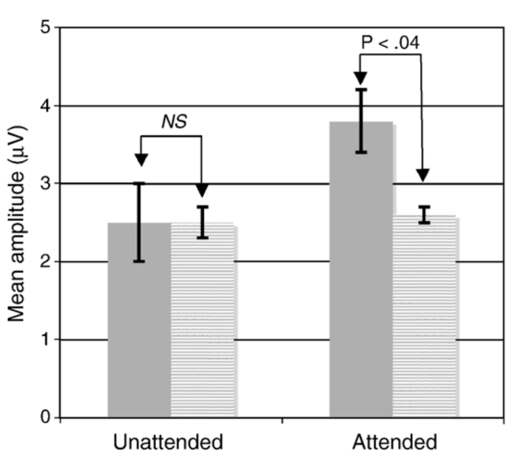

Fig. 3 – Mean amplitude from 100–200 ms of responses to unattended and attended probes. Error bars represent standard error of the mean. SLI and TD children did not differ in the magnitude of response to unattended stimuli. However, TD children showed a larger amplitude response than SLI children to attended stimuli.

2.2.2. *Individual difference in the attention effect*

Previous ERP studies suggest that group differences between SLI and TD children may only be characteristic of a subset of children, including those who are younger in age (Bishop and McArthur, 2004; McArthur and Bishop, 2005) or who also have poor performance on reading measures (McArthur and Bishop, 2004). The size of the attention effect (attended–unattended) is plotted for each subject in Fig. 4a. The data indicate variability within each group, as well as overlap between the two groups. Nine of the twelve SLI children scored below the lower-bound 95% confidence interval of the TD children, and eight of twelve scored at least one standard deviation below the mean of the TD children. This analysis also revealed one SLI child with a 1.0 μV *negative* attention effect, nearly two standard deviations from the mean of the other SLI children. To ensure that this child was not carrying the group effects reported above, all statistics were recalculated while excluding this child, with no change to the direction or statistical significance of the group results. All other children were within 1.65 standard deviations of their respective group mean.

Fig. 4b shows the correlation between the size of the attention effect and child age, separately for TD and SLI children. Across groups, size of the attention effect tended to show a modest correlation with participant age ($r = 0.37$, $P < 0.08$). In the TD group, this correlation was slightly larger, though nonsignificant given the small sample size ($r = 0.48$, $P < 0.12$). However, in the SLI group, age and size of the attention effect were not correlated ($r = 0.2$, $P > 0.5$), suggesting that age cannot account for variability among the SLI children.

Reading disability is not reliably diagnosed until children are older than most participants in the current study. However, with this caveat in mind, we can examine the reading scores of the older children (age five and above) who also completed the letter identification, word identification, and word attack subtests of the Woodcock Johnson reading battery (Woodcock, 1987, 1998). For the purposes of classification, children were labeled as having poor early literacy skills if they scored at least one standard deviation below the mean on the letter identification subtest or, for children over age 6;6, on the letter identification, word identification, or word attack subtest. Under this classification, four of the eight SLI children tested (50%) and one of the ten TD children (10%) had poor early literacy skills. The four SLI children with early literacy scores in the normal range were among the five SLI children with the largest attention effects. (The SLI child with the largest attention effect was four years old and did not complete the early literacy battery). The one TD child with poor early literacy skills had a typical, 1.0 μV positive attention effect. These data are suggestive, but far from conclusive, that attention deficits may be most characteristic of children with both language and reading deficits.

2.3. *Behavioral data*

To explore whether the group differences in early attentional modulation could be explained by on-task performance, responses to the 12 comprehension questions about the

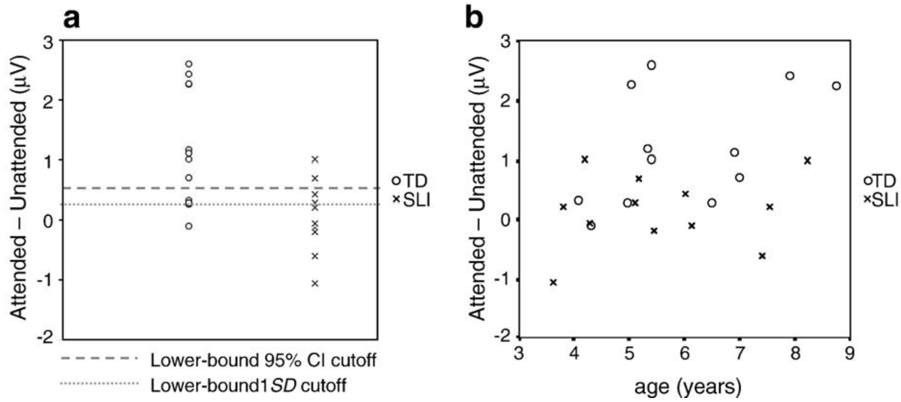

Fig. 4 – Graphs showing size of the attention effect (Attended–Unattended) from 100–200 ms for individual participants, collapsed across probe type. (a) Data from the TD and SLI groups. Dashed line represents the lower bound 95% confidence interval (CI) cutoff for the TD mean. Nine of twelve SLI children scored below this cutoff. Dotted line represents the lower bound one standard deviation (SD) cutoff below the TD mean. Eight of twelve SLI children scored below this cutoff. (b) Scatter plot showing size of the attention effect as a function of participant age, separately for TD and SLI children.

attended story were compared across groups. All children answered at least half of the questions correctly. There were no significant differences between groups in the number of comprehension questions correctly answered, independent samples $t(22)=1.5$, $P>0.15$; SLI $M=8.4$, TD $M=9.4$. Responses to the single question about the unattended story were at chance levels for both groups, one-sample $t<1$, both $P=0.6$, and did not differ between groups, Fischer's Exact $P=0.7$.

3. Discussion

These data are the first to show that SLI children have marked and specific deficits in the effects of selective attention on early neural processes. Whereas adults and TD children show attentional modulation by 100 ms, SLI children process attended and unattended auditory stimuli identically during early perception. This deficit in early attentional mechanisms was related specifically to lower levels of signal enhancement of attended stimuli. These findings complement the growing body of behavioral research (Asbjørnsen and Bryden, 1998; Atkinson, 1991; Cherry, 1981; Sperling et al., 2005; Ziegler et al., 2005) showing filtering deficits in children with language disorders. Furthermore, these data localize the timing of the attentional deficit in SLI to the earliest stages of processing that are typically modulated by attention.

Importantly, the neurophysiological deficits in attention were observed despite behavioral evidence that the SLI children were attending appropriately and willing to perform the task. The SLI and TD groups showed equivalent performance when answering comprehension questions about the attended story. In addition, indirect measures of children's motor and eye movements during the task showed no differences between groups. Although the carrier task in the present study was linguistic (i.e., listening to an auditory story), consistent with behavioral studies (Asbjørnsen and Bryden, 1998; Atkinson, 1991; Cherry, 1981; Sperling et al., 2005; Ziegler et al., 2005), filtering deficits were observed for both linguistic and nonlinguistic probe stimuli. Future work will need to examine whether these early attentional deficits are also observed in purely nonlinguistic tasks, as well as whether the early attentional deficits are compounded by additional deficits in later stages of processing (e.g., response selection).

The current study used a methodology modeled after classic ERP paradigms for assessing selective auditory attention (Hillyard et al., 1973). Critically, these paradigms include a competing channel of information that must be actively filtered, enabling the comparison of the same physical stimuli under conditions of attention and inattention, while controlling for arousal and task demands. It could be the presence of this competing information that, as in behavioral studies (Asbjørnsen and Bryden, 1998; Atkinson, 1991; Cherry, 1981; Sperling et al., 2005; Ziegler et al., 2005), creates the conditions for attentional deficits in SLI. Indeed, the absence of competing stimuli and the confounding effects of manipulating arousal could explain why the SLI children in the study by Shafer et al. (2005) show modulation during a similar time window, as well as the different polarity of effects observed in TD children in that study.

Analysis of individual subject data showed large variability in both the TD and SLI groups, as well as overlap in the performance of the two groups. This observation is consistent with the view that SLI is a heterogeneous disorder, represented by different profiles of deficits in different children. It is also consistent with the view that, like deficits in rapid auditory processing, selective attention deficits are neither necessary nor sufficient to produce SLI. The data suggest that a deficit in selective auditory attention may predispose, but not condemn, a child to language deficits. In some previous studies, variability in ERP performance in SLI children could be accounted for by participant age or performance on related behavioral tests. However, in the present data, variability in the size of the attention effect among the SLI children could not be accounted for by participant age. Although the young age of the participants in the current study precluded an extensive analysis of reading ability, the data did suggest that the subset of SLI children with attention effects within the normal range also had early literacy scores within the normal range. It will be important for future work to examine individual differences and attempt to account for the different profiles of deficits observed in different children.

It is interesting to consider how the ERP deficits in selective auditory attention observed in children with SLI relate to behavioral studies reporting attention deficits in dyslexia. It is known that language impairment and dyslexia have a 50% comorbidity rate (Bishop and Snowling, 2004; Catts, 1993; Eisenmajer et al., 2005; McArthur and Hogben, 2001). Thus, a study such as the present one designed to select children with SLI will, most likely, include many children who also have dyslexia. As noted above, the young age of our participants prevented us from assessing reading skills in all children. However, of the eight SLI children completing reading tests, four (50%) were at least one standard deviation below the mean on age-appropriate early literacy tests. One study of filtering deficits in dyslexic children reported that the deficits were largest among poor readers who also had poor oral language skills (Sperling et al., 2005). Further, some data suggest that abnormal evoked responses may be characteristic only of those SLI children who have poor reading skills (McArthur and Bishop, 2004). The analysis of individual subject data in the present study, which showed that children with only SLI or only poor early literacy skills generally had attention scores in the normal range, are consistent with this hypothesis. These data are suggestive that children with both SLI and reading disability may have additional, or more pronounced, deficits in particular domains.

Based on the current data alone, it is difficult to assess the functional significance of the absence of early attentional modulation in children with SLI. Indeed, the only behavioral measure collected during the task (responses to comprehension questions) showed no differences between groups. However, both the narrative stories and the comprehension questions were designed to be appropriate for children as young as 3 years of age. Further, the comprehension questions were included to encourage the child to pay attention to a single story, rather than as a sensitive assay of language or attention skills (which likely explains why both SLI and TD children had equivalent performance). However, when considered in the context of the behavioral studies showing deficits in attentional filtering among children with language disorders (Asbjørnsen and Bryden, 1998; Atkinson, 1991; Cherry, 1981; Sperling et al., 2005; Ziegler et al., 2005), it is reasonable to assume that the early ERP deficits have a behavioral consequence on attentional selection. We speculate that had a paradigm been used in which participants had to detect rare deviant tones in the attended channel or indicate whether each tone came from the attended or unattended channel, children with SLI would have shown behavioral impairments. Alternatively, it will be interesting for future studies to collect an offline behavioral measure of attentional filtering that can be correlated with performance on the ERP task. Such data may help explain individual differences in performance on the ERP task.

Poor attentional filtering could lead to deficits in a number of sensory, cognitive, and linguistic domains. For example, it has been suggested that deficits in noise exclusion might underlie putative M-pathway and rapid auditory processing deficits in dyslexia (Sperling et al., 2005). Related work from our laboratory suggests a possible mechanism whereby deficits in attention may influence speech processing by 100 ms: during online speech processing, ERPs to word-initial syllables are enhanced compared to acoustically identical word-medial syllables (Sanders and Neville, 2003; Sanders et al., 2002). This suggests that a similar early attentional modulation may play a role in parsing continuous speech streams. Ongoing work in our laboratory is exploring the relationship between speech processing and attention in both TD and SLI children.

There may be important clinical implications of an attentional deficit in SLI. For example, to the extent that attention deficits are causally related to language impairment—or to the extent that improved attention skills can compensate for language deficits—attention training might be expected to improve language and literacy skills. A recent study suggests that such training may be effective. Chenault et al. (2006) found that dyslexic adolescents showed greater gains following a 10 week writing intervention if they first received 10 weeks of attention skills training (as opposed to 10 weeks of reading fluency training). This suggests that training in attention helps children with language deficits benefit more from targeted instruction in an academic domain. In a different vein, it has been suggested the some language training programs may work by training children's attention skills (Gillam, 1999; Gillam et al., 2001; Sundberg and Lacerda, 2003). We are currently analyzing data from a training study to test this hypothesis. Our data suggest that both TD and SLI children have improved selective attention skills (as indexed by a larger amplitude ERP attention effect using the paradigm described here) after 6 weeks of daily training. The same attention gains are not observed in children not receiving training, but retested after a comparable amount of time. These data suggest that attention may be a tractable leverage point for intervention programs designed to improve children's language and literacy skills.

In summary, children with SLI do not show early attentional modulation of auditory sensorineural responses. The cascading effects of a deficit in early attentional mechanisms may help to integrate the large and disparate literatures reporting a diversity of sensory and linguistic deficits in SLI and dyslexia.

4. Experimental procedures

4.1. *Participants*

The final sample included 24 children (11 male; mean age 5.8 years, SD 1.5, range 3.6–8.8 years). All children satisfied the following inclusion criteria: (1) normal hearing (20 dB at 500, 1000, and 4000 mHz), (2) normal or corrected-to-normal vision, (3) monolingual, native English speaker, (4) absence of ADHD diagnosis, (5) not taking psychoactive medications, (6) no known neurological disorders, and (7) nonverbal IQ above 80 as assessed using the Stanford-Binet 5 nonverbal composite (Roid, 2003; one SLI and one TD child's nonverbal IQ was based on only the fluid reasoning subtest).

Twelve children who scored at least one standard deviation below normal (i.e., below the 17th percentile) on the CELF receptive language composite (Semel et al., 1995; Wiig et al.,

2004) and whose receptive language score was at least two-thirds of a standard deviation (10 standard scores) below their nonverbal IQ were classified as having specific language impairment (SLI). Nine of these children also scored below the 17th percentile on the CELF expressive language composite. One additional child with SLI was tested but excluded from analysis due to poor data quality, indicated by abnormal raw EEG responses and lack of any identifiable components in averaged data. Twelve children who scored above the 22nd percentile on the CELF receptive language composite were classified as typically developing (TD). The TD controls were selected from a larger database of participants included in our ongoing studies of typically developing children (Sanders et al., 2006) in order to match the SLI group in terms of age, gender, handedness, socio-economic status (SES), nonverbal IQ, and experimental conditions. Groups were compared on demographic and behavioral measures using two-tailed independent samples *t*-tests or, for nominal variables, Fischer's Exact Tests.

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.

4.2. Stimuli and procedures

The stimuli and procedures have been described in detail previously (Sanders et al., 2006). Briefly, two narrative stories were played simultaneously from separate speakers located to the left and right of the child, who was cued to attend selectively to one of the two narratives. The stories differed in location (left/right speaker), narration voice (male/female), and content. Small images from the attended story were presented on a central monitor (see Fig. 1). Each participant attended to a total of four 2.5- to 3.5-min stories (two from each speaker location). ERPs were recorded to linguistic (the CV syllable) and nonlinguistic (a broad spectrum buzz) probe stimuli (100-ms duration) embedded in the attended and unattended stories. The linguistic probe was the syllable /ba/, spoken by a female speaker (different from the female narrators) and then digitized and edited to 100 ms in duration. The nonlinguistic probe was created by scrambling 4- to 6-ms segments on the /ba/ stimulus. This resulted in a broad-spectrum 'buzz' sound that, while sounding nonlinguistic, preserved many of the acoustic properties of the linguistic probe. Across the four stories, 252 trials of each of the four probe types (linguistic/nonlinguistic × attention/unattended) were presented. The two stories were played at 60 dB SPL (A-weighted), and the probe stimuli were played at 70 dB. The interstimulus interval (ISI) between probes was either 200, 500, >or 1000 ms, and an equal number of probes at each ISI were presented. An adult experimenter sat next to the child at all times to administer instructions and monitor the child's behavior.

The SLI and TD children were balanced for attended story and attended start side (right or left). The groups were balanced to within one participant for attended story narration voice (male/female). One child each in the TD and SLI group was tested using a second stimuli set using stories from the *Max and Ruby* (Wells, 1991, 1997, 2000, 2002) and *Henry* (Johnson, 2000, 2002, 2003, 2004) series, read by a different male and female narrator. In this stimuli set, 201 trials of each of the four probe types were presented.

Behavioral and ERP assessments took place across 3 days of testing at the University of Oregon. Behavioral testing took place during two separate sessions and was supervised by a certified speech language pathologist. On a separate day, children visited the electrophysiology laboratory for ERP testing, described in detail below. All three testing sessions were completed within a 30-day time window.

To encourage the child to pay attention, following each story the experimenter asked the child three basic two-alternative comprehension questions about the attended story. Children could also answer 'I don't know," which was counted as an incorrect response. These questions were not designed as a sensitive assay of children's language abilities (this was the purpose of the standardized tests), but were instead included to reinforce to the child the goal of paying careful attention to a single story. After answering the three questions, the child heard another story concerning the same characters and read in the same voice. This procedure was repeated four times until the child had listened to four stories (attending twice to the left speaker and twice to the right speaker) and answered twelve comprehension questions. At the end of the experiment, the child also answered one basic question about the unattended story set.

4.3. Apparatus: 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. Additional electrodes were placed at the outer canthi of each eye and beneath the right eye to monitor blinks and eye movement. Online, electrodes were referenced to the right mastoid, and offline electrodes were re-referenced to the average of the left and right mastoid. Electrode impedances were below 10KΩ for eye electrodes, 5KΩ for scalp electrodes, and 3KΩ for mastoid electrodes. EEG was amplified 10,000 times using Grass 7P511 amplifiers (bandpass 0.01 to 100 Hz) and digitized online (250-Hz sampling rate). To reduce electrical noise in the data, a 60-Hz digital filter was applied offline.

To remove artifacts due to blinks, muscle movement, or eye movement, individual artifact rejection parameters were selected for each participant. Parameters were selected based on inspection of the raw data to identify the smallest change in amplitude observed during a blink (based on shape in EOG electrodes and reversal in polarity above and below the eye) or eye movement (based on shape and distribution). Muscle movement was assessed based on channel blocking.

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