Neurophysiological Indexes of Speech Processing Deficits in Children with Specific Language Impairment

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Abstract

■ We used neurophysiological and behavioral measures to examine whether children with specific language impairment (SLI) have deficits in automatic processing of brief, phonetically similar vowels, and whether attention plays a role in such deficits. The neurophysiological measure mismatch negativity (MMN) was used as an index of discrimination in two tasks; one in which children ignored the auditory stimuli and watched a silent video and a second in which they attended to the auditory modality. Children with SLI showed good behavioral discrimination, but significantly poorer behavioral identification of the brief vowels than the children with typical language development (TLD). For the TLD children, two neurophysiological measures (MMN and a later negativity, LN) indexed discrimination of the vowels in both tasks. In contrast, only the LN was elicited in either task for the SLI group. We did not see a direct correspondence between the absence of MMN and poor behavioral performance in the children with SLI. This pattern of findings indicates that children with SLI have speech perception deficiencies, although the underlying cause may vary. ■

INTRODUCTION

Acquiring a first language for most children is relatively effortless. However, for some children (5–10%), language abilities lag far behind their peers, particularly in phonological and morphophonological production (e.g., Bishop, 1997). Children with these language delays, but no evidence of frank neurological, sensorimotor, or nonverbal cognitive deficits are called specific language impaired (SLI). One possible cause of SLI is atypical development of speech perception. In a developmental model of word recognition, Jusczyk (1997) proposed that infants weight critical features of speech sounds that are necessary for making semantic distinctions and that these weightings result from the automatic focusing of attention on relevant features in the speech signal. These weighted representations are used to segment the speech stream into word-size units, which are then matched to stored representations of known words, or used to discover and store novel representations. Failure to select the relevant features for storage in long-term memory representations or limitations in the automaticity of feature selection result in poor segmentation skills, deficient phonological representations, and delayed word learning.

Many children with SLI have poor auditory processing, including deficiencies in discriminating and distinguishing the order of rapidly presented tones and speech sounds (Stark & Heinz, 1996; Frumkin & Rapin, 1980; Tallal, Stark, Kallman, & Mellits, 1980; Tallal & Piercy, 1974), in identifying/categorizing speech sounds (Sussman, 1993), and in identifying brief speech sounds presented in the context of relatively longer sounds (Leonard, McGregor, & Allen, 1992). These findings do not reveal the origins of these deficits or fully explain their impact on language acquisition. Furthermore, they do not distinguish between the possibility that children with SLI fail to store relevant speech features in long-term representations or have reduced automaticity in relevant speech feature selection.

The event-related potential (ERP) component mismatch negativity (MMN) provides a direct test of automaticity because it can be used to examine speech discrimination under different levels of attention. MMN is a preattentive index of change detection of a stimulus feature or pattern (Sussman, Ritter, & Vaughan, 1999; Näätänen, 1990). Furthermore, the amplitude or latency of MMN to a speech contrast is affected by the contrast's phonemic status in the listener's native language (Shafer, Schwartz, & Kurtzberg, 2004; Winkler et al., 1999; Näätänen et al., 1997). Specifically, the MMN is larger or earlier for a pair of speech sounds crossing a phonemic boundary compared with a pair within a phonemic

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category. The relevant cues for a phonemic distinction in a speaker's native language are automatically selected at a preattentive level.

Children with SLI or with broadly defined learning problems (LP, learning disability or attention-deficit disorder) have smaller MMNs to speech contrasts. Uwer, Albrecht, and von Suchodoletz (2002) observed significantly smaller MMNs in children with SLI to natural speech syllables differing in place of articulation (*/ba/*, */da/*, and */ga/*). Similarly, Kraus et al. (1996) observed smaller MMNs to synthesized [*da*] versus [*ga*] speech sounds in children with LP compared with those with typical learning skills. These findings support the hypothesis that children with SLI, as well as those with other learning disabilities, are less automatic in processing speech or that they incorrectly weight speech cues.

Although MMN can be elicited preattentively, attention can modulate its amplitude, particularly for difficult discriminations. Specifically, children showed an MMN to a difficult contrast only with attention (Gomes et al., 2000). Children with SLI might exhibit a larger MMN to a difficult speech contrast with attention, and thus, their selection of relevant speech features may be less automatic than that of their peers.

The purpose of the current investigation was to examine whether children with SLI have a deficit in the automaticity of speech processing or in correctly weighting relevant speech features. Eight children with SLI (referred by speech–language pathologists) and 11 children with typical language development (TLD) were compared. The children with SLI scored significantly lower on the Clinical Evaluation of Language Function (CELF-3) but not on the Test of Non-Verbal Intelligence (TONI). Table 1 presents the participants' language and nonverbal scores. In the ERP tasks, resynthesized 50-msec vowels ([*I*] in "bit" and [ε] in "bet") were presented in an oddball paradigm designed to elicit MMN. The children participated in two MMN tasks. In the passive task (typically used in MMN studies), they were asked to ignore the auditory stimuli and watch a video with the sound turned off. In the attend task, they were asked to press a button when a target tone was perceived among the vowel sounds. The participants performed two behavioral discrimination tasks: one task (D1 task) using the same oddball design as the ERP study (except slower stimulus rate of 2/sec) and a second task (D2 task) in which they had to decide if a pair of sounds separated by the same intrapair interval (550 msec) as the ERP study was the same or different. They were also asked to identify four exemplars of [*I*] and [ε] (ID task), including the two used in the ERP and behavioral discrimination tasks. These four exemplars varied in discrete, equal steps in F1 and F2 formant frequencies, which are the major cues of vowel perception. Two of the four stimuli at one end of the continuum were expected to be placed in the /*I*/ category, and the remaining two in the /ε/ category.

For children with typical language, we predicted robust MMNs to these vowel contrasts whether attention is directed to or away from the auditory modality, because they have learned to automatically weight the relevant features in English vowels for rapid identification. For children with SLI, we predicted small or absent MMNs when attention is directed away from the auditory modality. If these small or absent MMNs are because of a limitation in the automaticity of attentional focus on relevant speech cues, then we would expect to see an increase in MMN amplitude when attention is focused on the auditory modality. We also predicted that less automaticity in selection of relevant speech cues, but robust phonological representations, might lead to slower behavioral discrimination and categorization, but relatively good accuracy. Good accuracy was predicted in the behavioral tasks because the stimulus presentation rate was considerably slower on these tasks than the rates (<1 per 300 msec) shown to lead to deficits in auditory processing (Rosen, 2003). In contrast, if the deficit is related to incorrect weighting of relevant features in the phonological representations, then attention will have no effect on the MMN, because it will be directed to the incorrect features. Incorrect feature weighting would lead to poor speech sound categorization, but would affect behavioral discrimination less, because discrimination requires only that a pair of stimuli differ in at least one feature.

RESULTS

Behavioral Tasks

The children with SLI showed relatively good discrimination on the D1 discrimination task (6/8 of the SLI and 9/11 of the TLD discriminated >82%, Fisher Exact Test, $p = .4$), although they tended to perform more poorly than the TLD participants (3/8 SLI and 9/11 TLD discriminated >96%, Fisher Exact Test, $p = .07$). The SLI group also performed well on the D2 discrimination task (6/8 SLI and 8/11 TLD discriminated >90%, errors <10%, Fisher Exact Test, $p = .4$). In contrast, the SLI group displayed significantly worse performance on the identification task than the children with TLD (Fisher Exact Test, $p = .005$). Distinct phoneme categories are defined as greater than 72% categorization of stimulus 1 as [*I*] and stimulus 4 as [ε]. Poor categorization is defined by chance performance on one or both stimuli (identification between 33% and 73%). Only three of the eight children with SLI showed two distinct phoneme categories, whereas all of the TLD children showed distinct categories. No differences were observed in reaction time (RT) measures for any tasks ($t < 0.2$, $p > .84$). Table 1 shows the individual behavioral performance, the mean performance and standard deviation (*SD*) for the two groups (bottom).

Table 1. Individual Performance and Group Means (*SD*) on TONI and CELF-3 (Expressive, Receptive, Standardized Mean = 100), Percent Correct, and RTs (msec) for the D1 and D2 Behavioral Discrimination and Identification Tasks

Sub	*Age*	*TONI*	*Rec*	*Exp*	*D1 Dis*	*D1 RT*	*D2 Dis*	*D2 err*	*D2 RT*	*ID Stim 1*	*ID Stim 4*	*ID RT*	*Pas MMN*	*Pas LN*	*Att MMN*	*Att LN*
S01	9;11	113	84	84	93	589	90	0	646	47	73	664	No	Yes	No	Yes
S02	8;2	97	94	75	100	548	100	0	576	93	80	667	No	Yes	No	Yes
S03	10;9	90	100	78	60	567	100	0	647	33	40	530	Dev	No	Dev	Yes
S04	7;1	85	84	90	43	409	68	64	801	47	47	834	Yes	Yes	Dev	Yes
S05	8;11	94	88	96	100	453	86	36	588	47	73	484	Yes	Yes	Yes	Yes
S06	10;5	98	92	84	87	523	95	9	472	87	7	642	Dev	Yes	No	Yes
S07	10;7	NA	69	82	83	631	95	9	607	100	100	768	Dev	No	No	Yes
S08	8;10	89	104	78	97	449	100	5	542	93	100	888	No	Yes	Dev	Yes
N01	8;10	103	100	92	100	480	100	5	447	100	100	633	Yes	No	Dev	Yes
N02	8;9	105	104	135	100	410	95	0	468	100	93	466	Yes	Yes	Yes	No
N03	9;9	104	131	110	100	435	95	23	614	93	100	630	No	Yes	Yes	Yes
N04	8;8	93	104	100	97	437	95	0	544	93	87	807	Yes	Yes	Yes	Yes
N05	10;2	108	98	98	100	345	77	0	378	93	93	427	Dev	Yes	Yes	No
N06	8;0	89	110	120	47	697	91	1	684	73	87	933	Yes	Yes	Yes	Yes
N07	8;3	100	106	96	97	535	100	5	767	93	93	610	Yes	Yes	Dev	Yes
N08	8;11	100	104	108	100	633	100	0	956	93	100	746	Dev	Yes	Yes	Yes
N09	9;1	83	114	114	97	590	59	9	720	93	87	805	No	Yes	Yes	No
N10	8;1	100	102	104	57	740	95	9	730	80	80	813	Yes	Yes	Yes	Yes
N11	9;4	110	104	112	97	510	100	0	540	100	100	790	Yes	No	Yes	No
SLI mean	9;3 (1;4)	95 (9)	89 (11)	83 (21)	83 (21)	521 (77)	92 (11)	15 (23)	610 (96)	68 (27)	65 (32)	685 (140)	2	6	1	8
TLD mean	8;11 (0;8)	100 (9)	107 (9)	108 (12)	90 (19)	528 (125)	92 (13)	5 (7)	623 (169)	92 (8)	93 (7)	697 (157)	7	9	9	7

The last four columns indicate the presence and absence of a clear MMN and LN. Rec = Receptive; Exp = expressive; Dis = discrimination; ID = identification tasks; Yes = clear MMN or LN; Dev = deviant MMN; No = no MMN or LN; Stim = stimulus; Sub = subject; NA = not available (child referred as SLI with nonverbal scores in normal range by SLP, but would not perform the TONI). Numbers beginning with "S" are SLI and those beginning with "N" are TLD. Age is given in years;months. The ID RT is for labeling stimulus 1 as /ɛ/.

Mismatch Negativity Standard versus Deviant

Figure 1 displays the grand mean ERPs to the standard and deviant stimulus and subtraction waveforms at the right central site, C4, for the two groups in the two tasks. The morphology of the waveforms (large positivity, P100, peaking around 100 msec, followed by a negativity, N200–250 between 200 and 250 msec) is representative of the ERPs at the fronto-central sites (F3, Fz, F4, C3, Cz, and C4). The P100 and N200–250 peaks are obligatory components observed in the child's ERP only at fast rates of stimulus presentation (under 1 sec; e.g., Shafer, Morr, Kreuzer, & Kurtzberg, 2000). The ERP to the deviant stimulus was more negative than that of the standard beginning around 100 msec and extending almost to 300 msec in the children with TLD. Greater negativity of the ERP to the deviant was also observed for the children with SLI. However, the difference is particularly small in the attend condition. We performed four-way mixed analysis of variance (ANOVAs) to determine whether the standard and deviant (stimulus) differed across hemisphere (left, midline, and right), time (seven intervals between 100 and 310 msec), or group (SLI and TLD) at the frontal (F3, Fz, and F4) and central (C3, Cz, and C4) sites.

In the attend task at frontal sites, a significant four-way interaction including group was observed [Stimulus × Hemisphere × Time × Group: $F(12,204) = 3.113$, $p = .019$, $\varepsilon = .344$]. Step-down analyses examining each group separately revealed a significant main effect of stimulus for the TLD group [$F(1,10) = 11.179$, $p = .007$]. No significant effects including stimulus were found for the SLI group [stimulus: $F(1,7) = .001$, $p = .972$; Stimulus × Time: $F(6,42) = 2.248$, $p = .115$, $\varepsilon = .485$; Stimulus × Site × Time: $F(12,84) = 2.342$, $p = .101$, $\varepsilon = .254$]. At central sites in the attend task, interactions of Stimulus × Group approached significance [$F(1,17) = 3.537$, $p = .077$]. We also found a significant Stimulus × Hemisphere interaction [$F(2,34) = 3.492$, $p = .054$, $\varepsilon = .803$], reflecting that the stimulus difference tended to be larger over the right compared with left hemisphere sites.

In the passive task, a main effect of stimulus was found at frontal sites [$F(1,17) = 9.611$, $p = .007$] and central sites [$F(1,17) = 7.280$, $p = .015$]. No main group effects or interactions including group were observed in this task [frontal: Stimulus × Group, $F(1,17) = 3.243$, $p = .089$; all other effects with group, $p > .1$].

In summary, a significant difference between the standard and deviant was found for the TLD, but not the SLI children in the attend task at frontal sites. In contrast, in the passive task, the standard and deviant stimuli differed significantly, but group was not a factor.

Mismatch Negativity Topography

To confirm that significant differences observed between the standard and deviant ERPs are consistent with

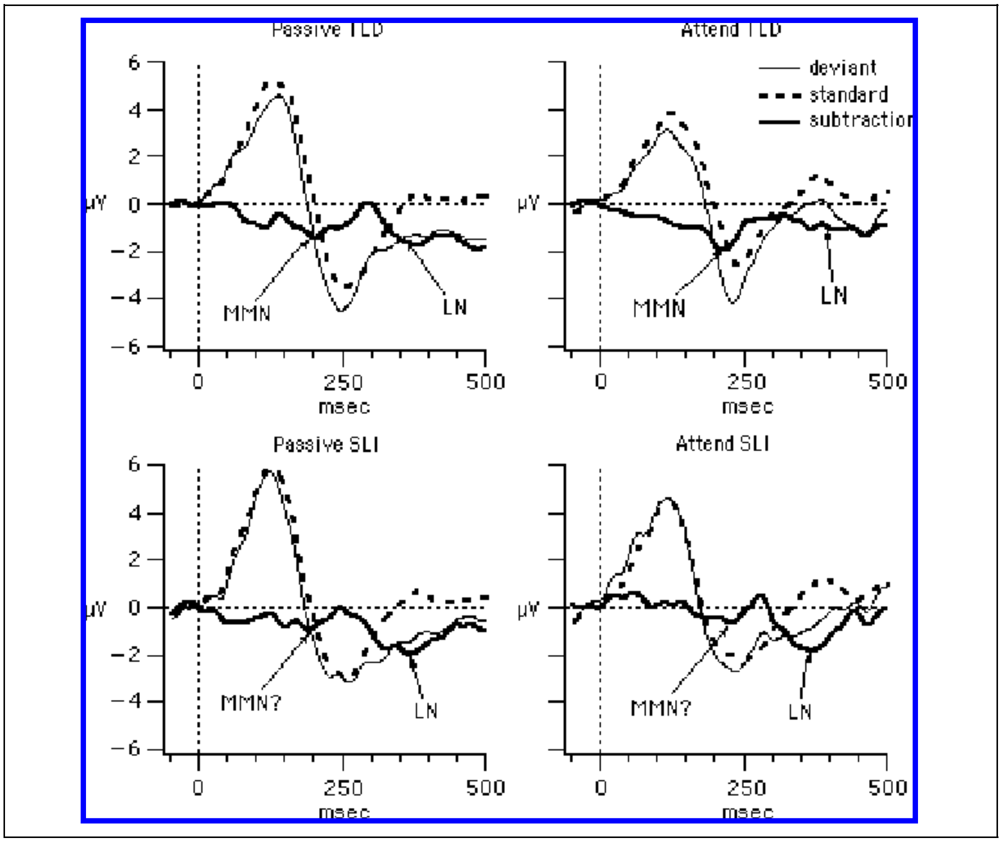

Figure 1. ERPs to the standard, deviant, and subtraction waveforms (deviant − standard) at C4. The peak negativities of the MMN and LN components are identified by arrows. The amplitude and the latency of the P100 component are nearly identical for the children with TLD and SLI.

MMN topography, we performed four-way ANOVAs using the subtraction waveforms (deviant − standard), with site (superior and mastoid), hemisphere (left and right), time (seven intervals), and group (SLI and TLD) as factors. A significant effect including site would indicate the presence of MMN. We expected clear evidence of MMN to be a negativity at the superior frontal and central sites (e.g., F3, F4, C3, C4) and an inversion, or relative positivity at inferior sites (mastoids; Näätänen, 1990). Figure 2 shows the subtraction waveforms of the standard and deviant stimulus ERPs at left and right superior sites (F3, C3, F4, and C4) and at the mastoids (left and right). Inversion of polarity (i.e., positivity) at the mastoids is present for the TLD group, but not for the SLI group. In the attend task, the four-way ANOVA revealed significant interactions of Site × Group

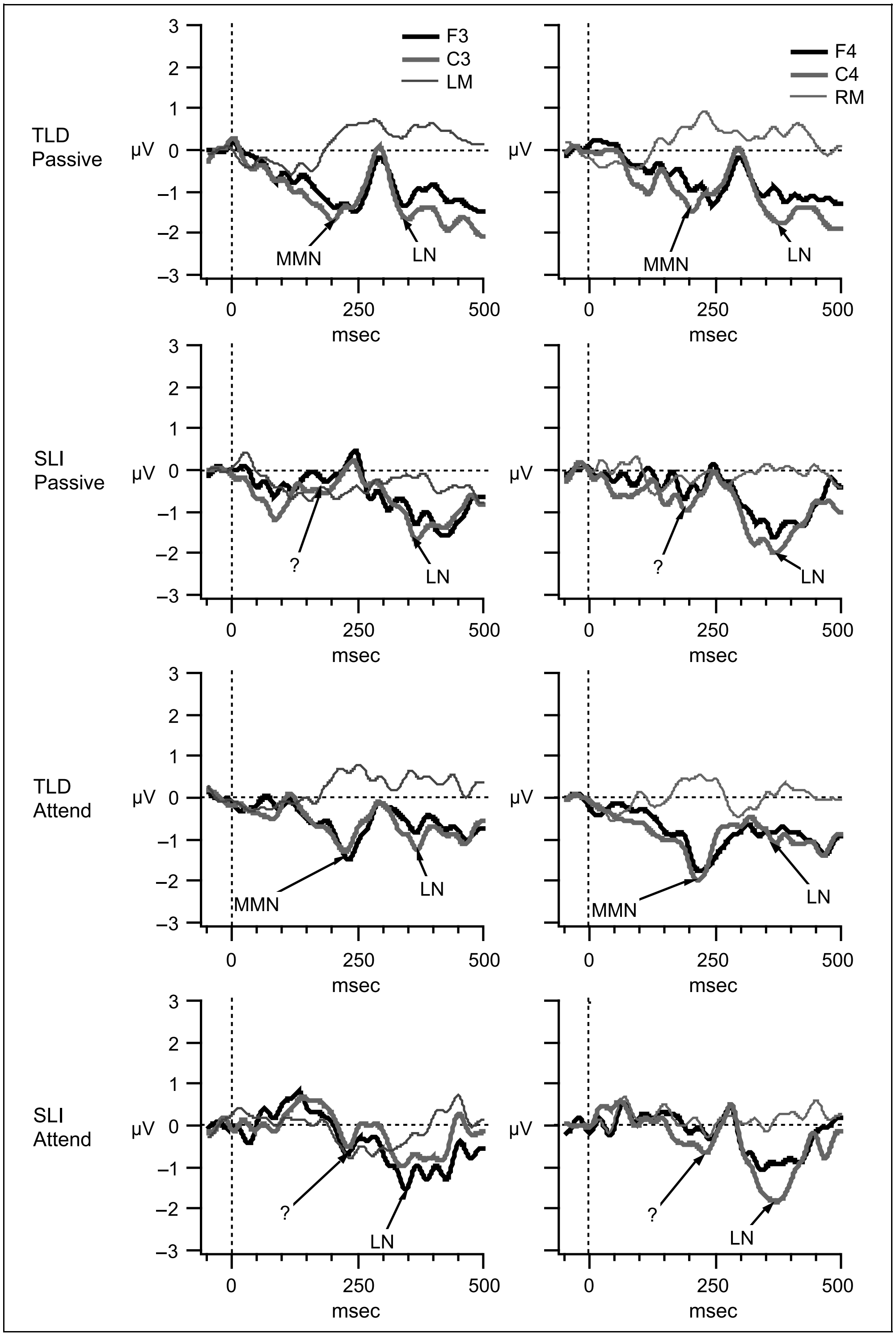

Figure 2. Grand mean ERP subtraction waveforms at left and right scalp sites for the two groups and two tasks. The children with TLD show negativity from 100 to 290 msec (MMN) and 350 to 500 msec (LN) at frontal (F3 and F4) and central (C3 and C4) sites with inversion at the mastoids (left [LM] and right [RM]). The children with SLI show a small negativity peaking around 200 msec; however, no inversion at the mastoids is observed. In contrast, they show a large LN similar to the children with TLD.

[$F(1,17) = 5.400, p = .003$] and Site × Time [$F(6,60), = 5.258, p = .010, \varepsilon = .458$]. We also observed an interaction of Hemisphere × Time × Group [$F(6,102) = 6.689, p = .000, \varepsilon = .651$]. In step-down analyses examining each group separately, the TLD group showed a main effect of site [$F(1,10) = 12.969, p = .005$] and a significant interaction of Site × Time [$F(6,60) = 5.258, p = .01, \varepsilon = .387$], for which the difference between sites was greatest for the intervals between 190 and 250 msec (see Figure 2). In contrast, for the SLI group the ANOVAs revealed a significant interaction of Hemisphere × Time [$F(6,42) = 2.809, p = .019, \varepsilon = .581$] and a Site × Hemisphere interaction that approached significance [$F(1,7) = 4.105, p = .055$]. We performed an additional step-down analysis (Site × Time) for each hemisphere separately to clarify these interactions for the SLI group. In these analyses, we observed a significant main effect only for time at left hemisphere sites [time: $F(6,42) = 4.087, p = .003$]. No other effect approached significance ($p > .39$).

In the passive task, the four-way analysis revealed a significant interaction of Site × Group [$F(1,17) = 9.311, p = .007$] and a main effect of hemisphere [$F(1,17) = 4.769, p = .043$]. Step-down analyses examining the groups separately show significant effects only for the TLD group [site: $F(1,10) = 18.710, p = .002$; hemisphere: $F(1,10) = 9.561, p = .011$; Hemisphere × Time: $F(6,60) = 4.170, p = .009, \varepsilon = .587$].

We also examined whether task (attend vs. passive) had an effect on the MMN in four-way analyses of Task (attend and passive) × Site (superior and mastoid) × Time (seven intervals) × Group (SLI and TLD) using the subtraction waveforms. These analyses did not show significant effects of task, but did confirm the Site × Group interactions observed in the previous analyses [left hemisphere: Site × Group, $F(1,17) = 15.724, p = .001$; right hemisphere: Site × Group, $F(1,17) = 7.768, p = .013$].

Individual Cases

One question arising from the absence of a significant MMN in the group data of the SLI children is whether an MMN can be observed in the individual cases. We had excellent signal-to-noise ratio because we delivered 400 deviants in each task, allowing us to examine individual

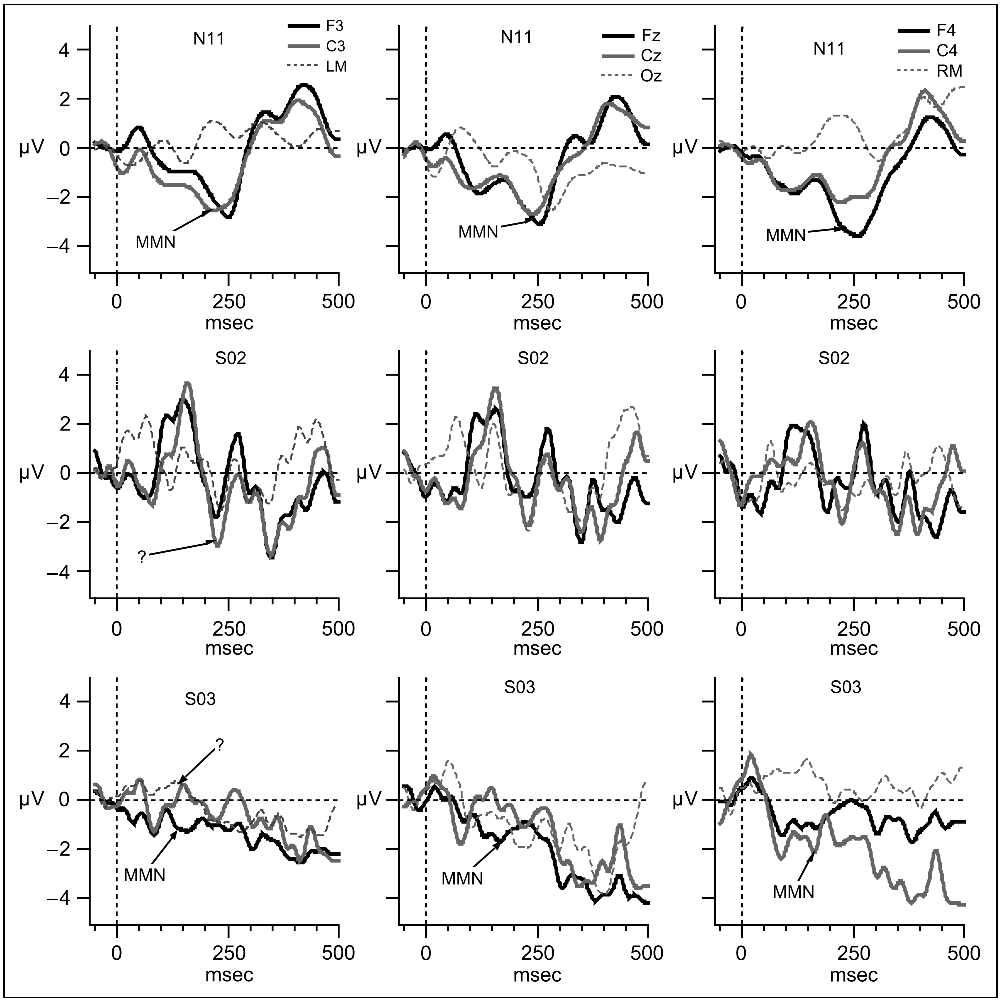

Figure 3. ERPs at left, central, and right sites for three children: one child with TLD (N11) demonstrating a clear MMN (negativity at F3, C3, Fz, Cz, F4, and C4; positivity at one or both mastoids); a second child from the SLI group (S02) showing no MMN (negativity at all sites, including mastoids), and a third child with SLI (S03) showing a deviant MMN (negativity, albeit small, in most, but not all frontal and central sites; positivity at one or both mastoids).

data. Only two of the eight children with SLI showed a clear MMN in the passive task and one of eight in the attend task. In contrast, 7 of the 11 TLD children showed clear MMNs in the passive task and 9 of 11 in the attend task. The proportion of children showing clear MMNs was significantly different for the two groups in the attend task (Fisher Exact Test, $p = .005$), but not in the passive task ($p = .115$). Figure 3 shows an example of a clear MMN (top), absent MMN (middle), and questionable MMN (bottom) for three children from the attend task. Table 1 shows the proportion of clear MMNs for the two groups, and the MMN classification for the individual children, along with scores on the TONI and CELF-3, and behavioral identification, discrimination, and RTs. As can be seen in this table, the two children with SLI showing clear MMNs, surprisingly, do not show good behavioral identification.

Task Differences

We also tested whether the two groups of children differed in their allocation of attention during the passive and attend tasks. Previous research has found a negative shift of the ERP (called the *processing negativity*, PN; Näätänen, 1990) beginning around 100 msec to an attended compared with unattended auditory stimulus. Four-way mixed ANOVAs of task (attend and passive) hemisphere (left, midline, and right), time (seven 30-msec time intervals from 101 to 301 msec), and group (SLI and TLD) examining the ERP to the standard stimulus were performed. A significant four-way interaction of Task × Hemisphere × Time × Group was found at the central sites [$F(12,204) = 2.504$, $p = .028$ $\varepsilon = .489$], as well as interactions of Task × Time for the frontal [$F(6,102) = 35.240$, $p = .000$, $\varepsilon = .387$] and central sites [$F(6,102) = 37.183$, $p = .000$, $\varepsilon = .385$]. To further examine the interaction including group at central sites, step-down analyses including task, hemisphere, and group were carried out for each of the seven time intervals separately. These revealed significant main effects of task for all the time intervals, except 190–220 msec [$F(1,17) > 5.381$, $p < .03$]. Greater negativity was observed for the attend task compared with the passive task for the intervals from 101 to 190 msec and greater positivity for intervals from 221 to 310 msec. From 131 to 160 msec, an interaction of Task × Hemisphere × Group [$F(2,34) = 4.208$, $p = .035$ $\varepsilon = .771$] and of Task × Group [$F(1,17) = 8.173$, $p = .011$] was also found. Tukey's post hoc tests revealed that both groups showed significantly greater negativity of the ERP in the attend task compared with the passive task in this interval ($p < .05$). However, the ERP at Cz and C3 in the passive task is also more negative for the TLD compared with SLI group (Tukey's HSD, $p < .05$; see Figure 4). In the later time interval (280–310 msec), the TLD, but not SLI group, show greater positivity of the ERP in the attend compared with passive task across all central sites (Tukey's HSD, $p < .05$; see Figure 4).

In summary, the ERP data provide evidence that both groups of children allocated greater attentional resources to processing the speech stimuli in the attend compared with passive task, as evidenced by the PN from 101 to 190 msec. The children with TLD also showed greater negativity than the children with SLI from 131 to 160 msec in the passive task. This suggests that they were attending to the speech stimuli, even in the passive task, but to a lesser degree than in the attend task.

Late Negativity

It is also important to note that most of the children in both groups showed greater negativity for the deviant compared with standard stimulus in a later time frame. This late negativity (LN) peaked at fronto-central sites between 300 and 500 msec, as can be observed in Figure 2. Four-way ANOVAs with stimulus (standard and deviant) hemisphere (left, midline, and right), time (six 30-msec intervals from 310 to 490 msec), and group (SLI and TLD) revealed significant main effects of stimulus [attend frontal: $F(1,17) = 6.196$, $p = .023$; attend central: $F(1,17) = 5.886$, $p = .027$; passive frontal $F(1,17) = 11.87$, $p = .003$; passive central: $F(1,17) = 21.53$, $p = .000$]. No effects including group approached significance ($p > .1$). Thus, both groups had significant

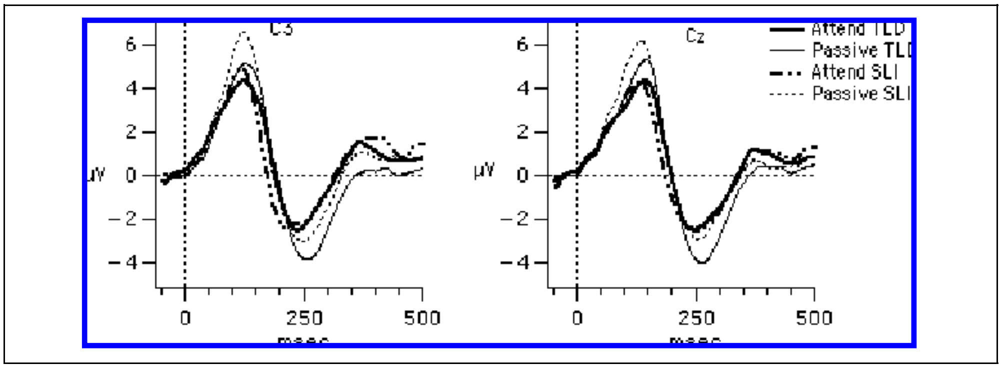

Figure 4. ERPs to the standard stimulus at C3 (left) and Cz (right). In general, the ERP to the standard in the attend task is more negative than in the passive task for both groups a superior frontal and central sites from 101 to 220 msec. However, it is also more negative in the passive task for the TLD compared with SLI group from 131 to 160 msec at Cz and C3.

negativities over frontal and central sites from 310 to 490 msec.

DISCUSSION

Most of the children with SLI, unlike most of those with TLD, showed no MMN in either the passive or attend task and most had poor behavioral identification. Both groups of children showed an LN component in both ERP tasks and good behavioral discrimination. We had hypothesized that reduced automaticity of attentional focus on relevant speech cues would result in a smaller or absent MMN in the passive task, but an increase in MMN amplitude in the attend task when attention is focused on the auditory modality. Limitations in automaticity would also lead to slower, but accurate, behavioral discrimination and identification. Thus, under this hypothesis, the child has an accurate representation with accurate weighting of relevant and irrelevant cues, and the deficit is in the automaticity of applying this representation in speech processing. Alternatively, we suggested that inaccurate selection of the relevant cues (i.e., incorrect weighting) would result in small or absent MMNs for both the passive and attend tasks, poor speech sound categorization, but relatively good behavioral discrimination. Our results are more consistent with this latter hypothesis. Below, we discuss our results in relation to findings from other studies and present arguments to support the hypothesis that as least some of the children with SLI in our study have incorrect weighting of features in their phonological representations.

Passive Task

A substantial body of evidence suggests that MMN is an index of automatic, preattentive change detection (Giard, Fort, Mouchetant-Rostaing, & Pernier, 2000; Ritter, Deacon, Gomes, Javitt, & Vaughan, 1995; Näätänen, 1990). The amplitude and peak latency of the MMN also reflect the difficulty of the discrimination, with easier discriminations leading to larger and earlier MMNs. The absence of an MMN in the passive task for the children with SLI suggests that the discrimination of the /*I*/ versus /ɛ/ contrast was more difficult for children with SLI compared with those with TLD, but does not reveal whether it is because of less automaticity in processing these stimuli or to a deficit in selecting relevant speech features. Our finding is similar to the results of Uwer et al. (2002), who observed a smaller negativity to a deviant consonant contrast in children with SLI compared with TLD. However, they examined a broad time interval that consisted primarily of what we are calling the LN response (320–650 msec for /*da*/ vs. /*ga*/ and 210–700 msec for /*da*/ vs. /*ba*/). A MMN-like negativity is seen in an earlier interval between 100 and 350 msec in Figure 1 of Uwer et al., but they did not test its significance. It is also not possible to conclude that the negativity (whether MMN or LN) in their study is an index of place of articulation discrimination (e.g., bilabial [*b*] vs. alveolar [*d*]) because the naturally produced syllables used in their study probably differed on other phonetic dimensions. Even so, their findings and ours suggest deficient speech processing. The finding (Bradlow et al., 1999; Kraus et al., 1996) that children with LPs show smaller MMNs to speech contrasting in brief consonant transitions (/*da*/ and /*ga*/) support the claim that deficient processing of speech is related to a wide range of LPs. However, the cause of this deficiency might be different for these populations.

In sum, the results of the ERP passive task reveal that children with SLI are deficient in processing speech. However, data from the ERP attend task, behavioral discrimination, and behavioral identification are necessary to choose between the two alternative hypotheses proposed above.

Automaticity in Feature Selection

We hypothesized that failure in selecting relevant cues automatically during speech processing would result in a small or absent MMN without attention directed to the auditory stimuli and a larger, clearer MMN with attention directed to the auditory modality. We also suggested that the limitations in processing automaticity might be seen as slower response times, but we did not expect it to lead to poor behavioral discrimination or identification at the slow rates of presentation (2 sec) used in this study.

The children with SLI in our study showed accurate discrimination, but poor identification and no difference in RT. Attention to the auditory modality also failed to lead to improved MMN. This pattern of results is not consistent with the hypothesis that speech perception deficits in children with SLI are due to limited processing automaticity, at least as the primary explanation. We were fairly certain that the children with SLI and TLD were allocating attentional resources to processing the speech stimuli in the attend task, because they showed a PN, which is elicited when attention is directed to a stimulus (Näätänen, 1990). However, it will be necessary to demonstrate that attention to speech features (by having a speech sound as a target) does not lead to a larger MMN in children with SLI before conclusively rejecting this as a contributing factor. It is possible that our fixed order (passive and attend) worked against finding a significant effect of attention on the MMN, because McGee et al. (2001) found that the amplitude of MMN declines over the time course of a long session. However, the PN in the attend condition does not support this possibility. The larger PN for the children with TLD compared with those with SLI suggests that this group is better able to divide their attention and, thus, allocate some attentional resources to the speech stimuli even when instructed to ignore them.

Incorrect Feature Weighting

As proposed above, a deficit in speech perception could be the result of incorrectly weighted phonological representations in memory. We hypothesized that this deficit would lead to small or absent MMNs in both the passive and attend tasks and poor behavioral identification. Behavioral discrimination would be relatively accurate because it only requires recognition of a single featural difference (not necessarily the category-critical feature) between stimuli. Our SLI group showed poor behavioral identification but relatively good behavioral discrimination, consistent with Sussman (1993). She found that children with SLI had accurate discrimination, but a different categorical boundary and a larger area of uncertainty for a place feature distinction (*/ba/* vs. */da/*) compared with TLD peers. We also found that attention to the auditory modality did not lead to a larger MMN in the SLI group. This pattern of findings appears to be consistent with incorrect weighting of relevant features. However, as will be discussed in the next section, only three of the eight individual cases show this predicted pattern for all ERP and behavioral tasks.

Incorrectly weighted representations would not support the trace-comparison process indexed by MMN. This explanation is consistent with investigations showing that the amplitude or latency of MMN is affected by experience with a language (Shafer, Schwartz, & Kurtzberg, 2004; Winkler et al., 1999; Näätänen et al., 1997). The weighted long-term memory representations clearly allow fast, automatic discrimination of speech sounds in adults, as indexed by MMN. In a current study, we are using the same vowel stimuli from this experiment to examine speech processing in early versus late learners of English with Spanish as a first language. We find that late learners of English, even if they appear to be proficient, show inaccurate identification and no MMN, but accurate behavioral discrimination. The monolingual and early bilinguals show MMNs and good behavioral discrimination and identification. Our SLI group showed a similar pattern of results to these late learners of English, suggesting they incorrectly weight the relevant features for categorization of these vowels.

The MMN is believed to index acoustic feature discrimination, but studies showing that native-language phonological categories affect the MMN suggest that the process indexed by this measure is linked to long-term phonological representations. In other words, accurate phonological representations lead to rapid selection of relevant cues for the comparison process. However, inaccurate representations do not preclude a preattentive trace comparison process, as demonstrated by studies using nonspeech stimuli. Thus, we expected, at least for the attend task, to see a neurophysiological response indicating discrimination, because children with SLI showed good behavioral discrimination. We did, in fact, see such a response, which we are calling the LN, in both the passive and attend tasks. Several other investigations using complex stimuli have observed a similar late discriminative response (e.g., Cheour, Korpilahti, Martynova, & Lang, 2001; Korpilahti, Krause, Holopainen, & Lang, 2001), and the significant negativity in the children with SLI and TLD in the study of Uwer et al. (2002) is at the later time interval of the LN. This LN may reflect a discrimination process that is independent of stored phonological representations and takes longer because evaluation of relevant features is not given priority over irrelevant features. In fact, the MMN and LN may reflect the same trace-comparison process, but the earlier negativity seen for the TLD group reflects the advantage of robust, accurately weighted phonological representations.

Individual Differences

The group data support the hypothesis that children with SLI have inaccurately weighted phonological representations. They also reveal that the absence of MMN and poor behavioral identification together serve as a sensitive marker for SLI. Every child from the TLD group showed good identification of the vowel stimuli and showed a robust MMN in at least one of the tasks,[1] which was not true for any of the children with SLI. However, individual differences across the children with SLI reveal a more complex picture. Only three of the eight children with SLI showed the pattern predicted to support incorrect weighting of relevant features, that is, poor behavioral identification and questionable MMNs. Of the remaining five, three showed good behavioral identification, but questionable MMNs. The accurate identification suggests that these children have selected and stored the correct relevant cues (i.e., have accurate weighting) in their long-term memory representations. The poor MMNs suggest that these three children are less automatic in using these representations. The larger MMNs we had predicted in the attend task may not have occurred because their attention was directed to detecting tones rather than identifying speech sounds. Alternatively, the processing of accurately weighted cues may have been slower (i.e., less automatic) for these children and was reflected in the later negativity of the LN. This explanation is supported by the slow RTs in the identification task for two of these three children.

Two other children with SLI showed a robust MMN (one of them in both tasks), but had poor identification and poor sensitivity on the D2 discrimination task. S04, who was the youngest child in the study, showed a robust MMN in the passive task, but not in the attend task. His poor performance on the behavioral tasks may have been partly due to age, but he has also shown poor performance on a phonological task at a later age (9 years, 8 months; Shafer, Schwartz, & Kessler, 2004). The other child (S05) with robust MMNs for both tasks exhibited very fast RTs and may not have taken the necessary time to evaluate the stimuli. This child was referred to us as SLI, but her relatively high language test scores and performance in this study suggest that the causal factors leading to her language deficits may be different from the other children with SLI.

These findings indicate that MMN and performance on the behavioral tasks do not reflect identical processes. This should not be surprising, because MMN indexes an early stage of processing, whereas behavioral discrimination and identification represent endpoints of processing. A number of processes and factors that support discrimination and identification may intervene between the earliest processing stages and these endpoint judgments.

The individual differences in the ERP and behavioral measures may have several different sources. However, a larger number of participants would be needed to explore these factors. It also may be particularly important to examine these individual differences in infants and toddlers because the core speech perception deficiencies that may be precursors to SLI may resolve or take different forms at later ages.

Poor Auditory Processing

One major debate regarding SLI is whether the cause of this disorder is a general auditory processing deficit or a deficit specific to speech or language (Bishop & MacArthur, 2005; Benasich & Tallal, 2002; Leonard, 1998; Tallal, Miller, & Fitch, 1993). Our study was not designed to test this question, because we did not examine processing of nonspeech auditory stimuli. Our findings, thus, do not rule out the possibility that poor auditory processing leads to speech perception and language deficits in some children. A deficit in auditory processing could affect the construction of long-term memory representations and, consequently, word learning, during development. However, poor auditory processing would not necessarily preclude developing adequate phonological representations or be the only causal factor in leading to deficits in phonological representations (see the work of Bishop, Carolyn, Deeks, & Bishop, 1999). The issue of whether children have a general auditory versus a speech specific deficit is of secondary interest. The more interesting question is how a deficit in auditory or speech processing might lead to the language LPs observed in children with SLI. A failure to correctly weight relevant features for identifying phonological categories or less automaticity can explain the delayed language learning and persistent phonological problems seen in many children with SLI. From a clinical perspective, under this view, intervention would be best directed toward highlighting the relevant features for rapid identification of the distinctive phonemes of the target language.

Conclusion

Our results suggest that many children with SLI have deficient speech perception abilities reflected in the absence of MMN and in poor behavioral identification. However, they also suggest that the origins of these speech perception deficiencies vary individually. Some have incorrectly weighted phonological representations in long-term memory as indicated by their poor categorization scores and absent MMNs, whereas others have less automatic or slowed processing, as reflected by good behavioral identification and robust LNs, but slow RTs and questionable MMNs. Accurate behavioral discrimination responses were seen in children with SLI despite questionable MMNs. This dissociation highlights the fact that behavioral responses made at the end of processes may involve other intermediate and less automatic processes. Our study illustrates that the use of neurophysiological measures in conjunction with behavioral measures can provide important insights into the nature of SLI.

METHODS

Subjects

We originally tested 18 children recruited as controls and 10 with language impairment. Two children were excluded from the SLI group. One had low nonverbal intelligence (<70 on the TONI) and one had a mild-to-moderate fluctuating hearing loss. We excluded seven children from the TLD group for the following reasons: five had TONI scores of >120, one had a TONI score of <70, and one had no language or nonverbal scores because she did not return for standardized testing. The children with SLI had no known neurological, sensory, or cognitive deficits other than language impairment, and were diagnosed by certified Speech Language Pathologists. All children received either the TOLD or CELF-3 to test their expressive and receptive language skills and the TONI to evaluate their nonverbal abilities. SLI children performed poorly on at least two subtests of the TOLD or CELF-3 (≤ 7, standardized mean score = 10) and scored significantly lower on the language tests (one-tailed $t > 4.0$, $p < .0001$), but not on the TONI than the control group (one-tailed $t = 1.2$, $p = .2$; see Table 1).

Stimuli

The stimuli were created by resynthesizing and editing a naturally produced exemplar using ASL/CSL software to produce a series of vowels perceived as either [*I*] in "bit" or [ɛ] in "bet." Formants F3 and F4 and the fundamental frequency F0 were identical for all stimuli, peaking at approximately 2714, 3175, and 190 Hz, respectively. The stimuli were edited to 50-msec in duration and had a rise and fall time of 5 msec. The four stimuli selected for this study had the following F1 and F2 formant frequencies: stimulus 1: F1 = 500 Hz, F2 = 2160 Hz; stimulus 2: F1 = 550 Hz, F2 = 2100 Hz, stimulus 3: F1 = 600 Hz, F2 = 2040 Hz; stimulus 4: F1 = 650 Hz, F2 = 1980 Hz. Stimuli 1 and 2 were consistently identified as the vowel [*I*] and stimuli 3 and 4 as the vowel [ɛ] by a group of nine adults. The intensity of the stimuli was set at 86.5 dB SPL.

Procedure

Behavioral

The children participated in three behavioral discrimination tasks (3-deviant [3D], 1-deviant [D1], and same–different judgment [D2]) followed by a behavioral identification task. In this article, we report the behavioral results of the Identification (ID), D1, and D2 tasks. (Results for D3 were similar to the D1 task.) In the identification task, each of the four vowel stimuli was presented 15 times, for a total of 60 stimuli. Participants pressed one button if they heard the vowel /*I*/ and a second button if they heard the vowel /ɛ/. In the D1 task, stimulus 4 occurred on 79% of the trials, and stimulus 1 on 21% of the trials (with a total of 30 deviant trials). Participants pressed a button for any stimulus that differed from the standard frequent stimulus /ɛ/. The stimuli were presented at a rate of 1 per 2 sec in the ID and D1 behavioral tasks. In the D2 (same − different) task pairs of stimuli were presented with an interstimuli interval of 550 msec (rate = 1 per 600 msec). The interpair interval was 2 sec. Practice trials were given for all tasks. RTs were compared using *t* tests, and the accuracy of behavioral data was compared using the nonparametric Fisher Exact Test (Siegel, Castellan, & Castellan, 1990).

Event-related Potential

ERP indexes of discrimination were examined in two tasks (passive and attend). In both tasks, stimulus 4 occurred on 79% of the trials and stimulus 1 on 21% of the trials (with a total of 400 deviant trials). Thirteen 50-msec tones were pseudorandomly embedded in each block of 500 speech stimuli to serve as targets in the attend condition. The stimuli were presented at a rate of 1 per 600 msec. In the passive task (most widely used in previous MMN investigations), the participant was instructed to ignore the stimuli and watch a video with the sound turned off. In the attend task the participant was instructed to press a button when they heard a target tone in the stream of auditory stimuli. The children were rewarded with an M&M candy for correct responses. A familiarization test was provided before the attend condition to ensure that the child understood the task. The passive condition always preceded the attend condition.

Recording System and Analysis

The electroencephalogram was sampled at 512 Hz from 31 scalp sites, referenced to the nose at a bandwidth of 0.05–100 Hz. An electrode placed 1 cm below the eye and referenced to Fp1 was used to monitor eye movements. The epochs of the electroencephalogram time-locked to the onset of stimuli were averaged and digitally low-pass-filtered at 30 Hz. Epochs with artifact greater than 100 μV were rejected from the average. The mean of the 50-msec prestimulus activity was set to 0 μV.

ANOVAs were performed using the mean amplitude of seven consecutive 30-msec time periods from 101 to 310 msec to test for significant negativity in the MMN time range, and using the mean amplitude of six 30-msec intervals from 310 to 490 to test for the LN. To examine whether the ERPs to the standard and deviant stimuli differed significantly, separate ANOVAs were performed for frontal sites (Fz, F3, and F4) and central sites (Cz, C3, and C4) with stimulus (standard and deviant), hemisphere (left, central, and right), and time (seven levels for MMN and six levels for LN) as within-subject factors, and group (TLD, SLI) as the between-subject factor. Step-down ANOVAs were performed to follow-up significant interactions.

To examine whether a significant difference between the standard and deviant could be considered an MMN, four-way ANOVAs including site (superior and mastoid), hemisphere (left and right), time (seven levels), and group (TLD and SLI) as factors were performed using subtraction waveforms. Subtraction waveforms were derived by subtracting the ERP to the standard from that of the deviant. The superior site measures were computed as the average of left frontal and central (F3 and C3) and right frontal and central (F4 and C4) sites. A four-way ANOVA including task (attend and passive), site (superior and mastoid), time (seven levels), and group as factors was performed on the subtraction waveforms of the left and right hemispheres, separately, to examine effects of attention on the MMN.

The subtraction waveforms were visually inspected and classified as clear, deviant or absent MMN. A clear MMN was defined as the presence of negativity at fronto-central sites (F3, Fz, F4, C3, Cz, and C4) and relative positivity at the mastoids (left and right) between 100 and 300 msec in the subtraction waveform. A deviant MMN was defined as the presence of negativity at most, but not all of the fronto-central sites (F3, Fz, F4, C3, Cz, and C4) and relative positivity at the mastoids (left and right) between 200 and 300 msec. No MMN was defined as an absence of negativity at frontal central sites or negativity at both fronto-central and at mastoid sites.

Group differences in the proportions of clear versus deviant or absent MMNs were examined using the nonparametric Fisher Exact Test.

To examine the PN, four-way mixed ANOVAs of Task (attend and passive) × Hemisphere (Left, Midline, and Right) × Time × Group were performed for the ERP to the standard stimulus at frontal (F3, Fz, and F4), and central sites (C3, Cz, and C4) on the mean amplitudes of seven 30-msec intervals between 101 and 310 msec. All analyses were performed for the two tasks (attend and passive), separately, except where task is listed as a factor. Tukey's HSD was used for pairwise comparisons. The Greenhouse–Geisser (ε) was calculated for all ANOVA analyses having greater than two levels.

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Note

1. This observation is also true for the six TLD children excluded from these analyses because of high or absent scores on the TONI (see Methods section).

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