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Evidence of Deficient Central Speech Processing in Children with Specific Language Impairment: the T-Complex

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Abstract

Objective—This paper examined neurophysiological correlates of speech in children with language impairment (LI) and typical language development (TLD) across four experiments using different speech stimuli and tasks.

Method—The T-complex event-related potential (ERP) components and other ERP components (e.g., mismatch negativity [MMN]; N400) were examined. A subset of the children participated in more than one of the experiments.

Results—73% of the children with LI had poor T-complex measures compared to only 13% of children with TLD. The T-complex measures were more comparable, in terms of indicating typical versus deviant processing, to neurophysiological measures of language processing, such as lexical discrimination, than to other measures of auditory and speech processing, such as the MMN. Only one LI child showed no poor measures and 64% showed three or more poor neurophysiological measures. However, 50% of children with TLD showed no poor neurophysiological measures, and 82% of the TLD children showed no more than two poor measures.

Conclusion—These results suggest that poor auditory processing, as measured by the T-complex, is a marker for LI and that multiple deficits serve to mark LI.

Significance—The T-complex measures, indexing secondary auditory cortex, reflect an important aspect of processing in speech and language development.

Keywords

Specific Language Impairment (SLI); Event Related Potentials (ERPs); T-complex; auditory development

Introduction

Research over the past two decades has confirmed that at least some children with specific language impairment (SLI) show deficits in auditory processing (e.g., Bishop, Carolyn, Deeks, & Bishop, 1999). Even so, it remains unclear how these deficits are related to the language impairments that are characteristic of SLI. The current definition of SLI generally requires children to perform at least 1.5 SD below the mean on at least some portion of a

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standardized language test (e.g. two subtests of the Clinical Evaluation of Language Fundamentals, CELF) and to perform within 1 SD of the mean on a non-verbal IQ test, such as the Test of Nonverbal Intelligence (TONI). Exclusionary criteria include no apparent neurological or hearing deficits or unusual history (e.g., prematurity, low-birth weight). Examination of the specific language difficulties of children identified as SLI in this manner reveals that many of them have poor phonological abilities (production and perception), deficits in production of inflectional morphology, syntactic comprehension or production deficits, smaller and more poorly elaborated lexicons along with language-related cognitive deficits such as working memory, attention, and executive functions (Leonard, 1998; Schwartz, 2009). However, there is considerable variability in the set of language and related deficits found for any one child with SLI. A number of different proposals have been offered to account for SLI and have had some success in characterizing subsets of children. For example, many, but not all children with SLI have deficits in phonological working memory (e.g., Gathercole & Baddeley 1990; Marton & Schwartz, 2003) and many (not necessarily the same ones) have deficits in verb inflectional marking (e.g., Rice & Wexler, 1999).

The heterogeneity of deficits suggests that no one cause will be shown to underlie SLI. A useful approach to understanding this disorder is to look for factors that serve as common markers of SLI, even though no single factor will contribute to all cases of SLI. For example, poor auditory/speech processing abilities have been identified in children across a number of studies (e.g., Tallal, Miller & Fitch 1993; Bishop, et al. 1999;). This poor processing frequently co-occurs with poor language development. Once a marker is identified as being common in SLI, it is then necessary to examine what additional factors co-occur, because it is likely that multiple factors contribute to language impairment.

There has been a long history of controversy regarding the extent to which poor auditory processing, or what has been termed poor temporal processing, contributes to SLI (Tallal, et al., 1993; Bishop et al., 1999; Rosen, 2003; Schwartz, 2009 for review). Some of the controversy relates to what is meant by temporal processing (and specifically to “rapid” changes in temporal information, see Rosen, 2003) and some to the interpretation of study results. Irrespective of the position taken on this controversy there is clear evidence that many children with SLI perform more poorly than typical controls on a number of auditory and speech processing tasks. Two questions arising from this finding are 1) How predictive is speech processing of language abilities? 2) What is the nature of the relationship between speech processing and language ability?

Of additional interest is what factors may serve to compensate for poor auditory processing. A number of studies have shown that a subset of children who show poor performance on auditory and/or speech processing measures have language abilities within the normal range (Bishop et al., 1999). These findings suggest that higher-level perceptual or cognitive processes interact with lower-level auditory/speech processing in ways that can contribute to or avoid poor language processing.

The purpose of this report is to examine to what extent auditory evoked potentials (AEPs) recorded at temporal scalp sites (the T-complex), and presumably indexing a fairly low-level of cortical (central) auditory processing, reveal a deficit in language. The T-complex indexes auditory processing with a probable source in lateral aspects of secondary auditory cortex (e.g., Ponton, Eggermont, Khosla, Kwong & Don, 2002) and has been linked to developmental disorders in several studies (e.g., Mason and Mellor, 1984; Tonquist-Uhlen, 1996). A secondary goal is to examine the relationship of T-complex measures to other measures of speech and language (both neurophysiological and behavioral) with regards to language outcome. Few studies have examined neurophysiological correlates of speech and

language processing in children with SLI, although the number is increasing (see Tropper & Schwartz, 2009). Some studies have shown atypical neurophysiological responses related to lower-level cortical auditory processes (e.g., Bishop & McArthur, 2004), and others have observed atypical processing related to higher-level cognitive functions, such as attention (e.g., Stevens, Sanders & Neville, 2006) or language (e.g., Shafer, Schwartz, Morr, Kessler & Kurtzberg, 2000). For the most part, these studies focused on one or two neurophysiological measures and did not, or could not attempt to relate lower-level neurophysiological indices of auditory/speech processing to higher-level indices of speech and language. One goal of this paper is to examine how lower- and higher-level neurophysiological measures of speech and language are related to language ability. To do this the data from four experiments (Shafer, et al., 2000; Shafer, Schwartz & Kessler, 2004; Shafer, Morr, Datta, Kurtzberg, & Schwartz, 2005; Datta, Shafer, Morr Kurtzberg & Schwartz, 2010) focusing on different levels of processing in children with SLI were re-examined in terms of a lower-level measure of cortical auditory processing, the T-complex. The T-complex peaks can be clearly identified in ERPs to the different stimulus types and tasks in the four experiments, unlike some other obligatory components, such as N1b, which is highly attenuated at rapid rates of presentation. The levels of processing examined across these four experiments were automatic pre-attentive speech discrimination, lexical-phonological processing, and sentence processing in discourse. The patterns of processing found in children with SLI for the event-related-potential (ERP) components indexing these levels of processing will be described below.

MMN as an index of discrimination in SLI

The mismatch negativity (MMN) is an ERP component that indexes automatic preattentive discrimination of auditory information (Näätänen, Paavilainen, Rinne & Alho, 2007). In several studies, children with SLI or learning problems have smaller, later or absent MMNs, particularly to relatively short duration speech information (e.g., Bradlow, Kraus, Nicol, McGee, Cunningham, Zecker, & Carrell, 1999; Uwer, Albrecht, & von Suchodoletz, 2002; Shafer, et al., 2005; Datta, et al., 2010). Specifically, in Shafer et al. (2005) and Datta et al. (2010), many children with SLI showed poor or absent MMNs to 50-ms tokens of the vowels [I] in “bid” and [E] in “bed”, but robust MMNs to 250-ms versions of these vowels. This pattern of findings was observed whether the children were attending to the auditory stimuli or ignoring them and watching a silent video. The MMN appears to reflect a fairly late process of discrimination compared to N1b and could be poor or absent for reasons other than poor auditory discrimination, such as poor representations of phonological information in long-term memory (Shafer, et al., 2005, Coady, Kluender & Evans, 2005). The finding that, regardless of vowel length and whether a robust MMN was elicited, about half of the children with SLI (and no adult or child with typical language) showed poor identification of the vowels in the studies by Shafer and colleagues indicates that poor speech processing as indexed by MMN is not sufficient to explain the poor behavior.

ERP indices of lexical access in SLI

The N400 ERP component serves as an index of lexical access and semantic integration. More difficulty in accessing a word results in a larger posterior negativity, peaking around 400 ms, which is called the N400. Thus, the more expected a word is, given preceding information (a prime or the sentence context) the smaller the N400. Sabisch and colleagues found that children with SLI did not show the typical N400 effect for anomalous verb selections (Sabisch, Hahne, Glass, von Suchodoletz & Friederici, 2006). Specifically, the children with SLI showed equally large negativity for the correct and incorrect verb selections, suggesting weaker representations of the verbs. A similar finding was seen for fathers of children with SLI (Ors, Lindgren, Berglund Hägglund, Rosén & Blennow, 2001). In contrast, in the case of identity priming (where an auditory word form is repeated, e.g.,

bed-bed) compared to a change of one speech sound (e.g., bed-ged), children with SLI and those with typical language show similar attenuation of an N400-like component to identity pairs (e.g., bed – bed) and equally-large, but significantly later peak latency of the N400 for prime and target words differing in onset consonants (e.g., bed vs. ged) (Shafer, et al., 2004). For word pairs differing in the final consonant (e.g., chief-chiev), however, only the children with typical language consistently showed evidence of the N400. A large posterior positivity overlapped with the N400 and was significantly greater for target words that differed than for targets that were the same as the prime for children with TLD, but not for children with SLI.

The children had been asked to make a behavioral decision by pressing one button if the words were the same (e.g., ged – ged), and a second button if they were different (e.g. ged-bed). Pairs of words that differed always consisted of one real word and one nonsense word in both orders (e.g., ged-bed or bed-ged). Behaviorally, the children with SLI made significantly more errors in judging whether a pair of words was different for words differing in the final consonant, regardless of order, and for the nonsense-real pairs that differed in the onset consonant. In terms of response reaction times (RT), the general pattern found for the behavioral responses in adults (who served as a control) and TLD children was to wait until the end of the word when presented with the nonsense-real order, even when the difference was in the onset (Shafer, et al., 2004). Many of the children with SLI did not show this pattern and responded faster for onset than final differences for the nonsense-real order. This difference in response patterns suggests that they were engaging different information, processes or strategies to perform the task.

The phonological N400 occurs relatively late in processing (after 200 ms) and probably indexes a process of comparing information in phonological memory to stored lexical representations. Any delays or deviances in this component can be entirely independent of poor auditory or speech processing. The late positive component (LPC) is probably from a class of components reflecting the decision process. Other studies have observed this component in lexical decision tasks and found that it overlaps with the N400 (e.g., O'Rourke & Holcomb (2002), as we observed in our study. The failure to find greater LPC for different compared to same pairs in children with SLI suggests greater difficulty for them in this task. The different response pattern to the nonsense-real word order differing in onset for the SLI compared to TLD group is arguably related to lexical, and not auditory deficits, since the TLD group show slower responses that we suggest indicate that they are waiting to complete lexical access. However, it remains possible that poor auditory processing is related to poor lexical learning in some fashion.

ERP indices of sentence-level language processing in SLI

Children with SLI also show neurophysiological differences in the amount of left versus right hemisphere engagement in language processing. In another study, Shafer and colleagues found a deviant pattern of ERPs for children with SLI in processing the determiner “the” at the onset of sentences in story and nonsense contexts (Shafer, et al., 2000). Specifically, an increased right temporal positivity and reduced left temporal positivity were found between 200–400 ms for the children with SLI compared to those with TLD. In addition, most of the children with SLI failed to show a superior central positivity that was found for children with TLD in this time range. These ERP patterns are fairly late in time (after 200 ms) and appear to be more related to aspects of language processing than lower-level auditory and speech processing. A study with adults using the same stimuli led to the suggestions that the right-hemisphere activity is related to discourse processing, and the left to grammatical aspects of processing (Shafer, Kessler, Morr, Schwartz, & Kurtzberg, 2005). Whether poor auditory processing contributed to this pattern of processing remains unanswered.

Auditory Evoked Potentials (AEPs) as indices of SLI

A few studies have found evidence for deviant processing of obligatory components (e.g., P1-N1-P2 measured at superior sites) in children with language impairment that reflect earlier stages of cortical processing (Tonnquist-Uhlen, 1996; Bishop & McArthur, 2005; Shafer, Ponton, Datta, Morr, & Schwartz, 2007). In particular, Shafer, et al. (2007) found evidence of delay in the P100 component in children with SLI and evidence that these children may be allocating their attention differently than children with TLD to speech information. The delay in P100 could possibly indicate poor speech processing; however, differences in how attention modulates this component could also explain the result (Shafer, et al., 2007). Both the N1 (more specifically, N1b) and P1 components can be difficult to compare across studies using different stimulus and task designs because N1b is highly refractory in children at rates of presentation less than 1 second, leading to absence of a clear peak (e.g., Shafer, et al., 2007). In its absence, the P1 and P2 peak merge into one peak, the P100 (see Shafer, et al., 2007) again making it difficult to compare P1 across studies with different stimulus presentation rates.

T-complex measures as indices of language impairment

A different series of obligatory components, the T-complex also appears to reflect auditory or speech processing and the processes measured by these components may be critical for good speech perception, as suggested by Tonnquist-Uhlen and colleagues (Tonnquist-Uhlen, Ponton, Eggermont, Kwong & Don, 2003). Two studies have shown abnormalities in the T-complex in children with severe language impairments (e.g., Mason and Mellor, 1984; Tonnquist-Uhlen, 1996). The T-complex indexes encoding at an early level of central auditory processing (CAP) between 50 and 200 ms. Abnormalities in these components are likely to indicate abnormal auditory or speech processing.

The T-complex is a sequence of AEP components measured at electrode sites over the lateral temporal cortices (Tonnquist-Uhlen, et al., 2003). Dipole source modeling suggests that the cortical sources of the T-complex are at least partially independent of the obligatory P1, N1 and P2 measured at superior (dorsal) fronto-central scalp sites (Ponton et. al, 2002). The T-complex consists of a sequence of three peaks between 70 and 160 ms in adults (e.g., Wolpaw and Penry, 1975; McCallum and Curry, 1980). The negative polarity peak Na, occurs from 70–80 ms; the positive-going peak Ta from 80–100 ms and the negative-going peak Tb, from 140–160 ms. Children show similar or slightly later latencies compared to adults for the T-complex, when measured at the lateral temporal sites T7 and T8 (T3 and T4 in the older 10–20 labeling system) (Tonnquist-Uhlen, et al., 2003). Tonnquist-Uhlen and colleagues (2003) suggest that sites T7 and T8 are optimal for measuring the T-complex because they reflect little activity from the sources underlying the P1, N1 and P2 (see Martin, Tremblay, & Stapells, 2007; Martin, Tremblay & Korczak 2008; for a review of P1, N1, P2).

The Present Study

The present study examines the T-complex index of auditory processing of speech stimuli in 31 children with typical language development (TLD) and 22 children with language impairments (LI) and relates this component to other neurophysiological and behavioral measures. These children participated in one or more (up to four) electrophysiological studies using speech stimuli at Albert Einstein College of Medicine (AECOM) conducted over a period of five years (Shafer, et al., 2000; Shafer, et al., 2004; Shafer, et al., 2005; Shafer, et al., 2007; Datta, et al., in press). This allows us to examine the stability of the T-complex measures across studies and in the same child, but elicited to different stimuli and at different ages. We also have a great deal of behavioral and electrophysiological data for the children participating in multiple studies, which allow construction of detailed profiles

for these participants and allow us to begin to address the question of the relationship between lower (e.g., auditory) and higher (e.g., lexical) level processes in language impairment. A second goal of this report is to examine which methods of T-complex measurement best identify group membership, as well as to determine which methods can be applied with the greatest ease in terms of time and measurement objectivity.

Our major hypothesis was that children with SLI (or LI) would show poorer T-complex measures, realized as less prominent peaks, or as later latencies. We had no clear guidance from the literature on how strongly the T-complex measures would be related to other neurophysiological measures obtained from these children. However, a reasonable hypothesis is that T-complex measures, if they are indexing fairly low-level cortical auditory processing, will show a stronger relationship to other neurophysiological measures that are tapping into sound processing, such as the MMN, and P100 measures, compared to measures tapping into higher-level processes, such as lexical access (e.g., N400), or sentence processing (e.g., late positivities). It is also possible that the heterogeneous nature of SLI will be confirmed in this study in that we will not find strong relationships between different measures; rather, we may find that SLI children show multiple, but not identical poor measures, whereas children from the TLD group will show robust processing for the majority of measures.

Method

Overview

The children participated in four different studies. These are described in the order in which they were conducted. The first study consisted of ERPs time-locked to the Determiner *the* in story, nonsense and repetition conditions and will be referred to as the determiner (DET) study (see Shafer, et al., 2000). The second and third studies used short and long version of the [I]/[E] vowel contrast and will be referred to as the Short Vowel (SV) and Long Vowel (LV) studies (see Shafer, et al., 2005; Shafer, et al., 2007 and Datta, et al., 2010). The fourth study used real content words (e.g., “bed”) and phonologically-similar nonsense forms (e.g., “ged”) and will be referred to as the Content Word (CW) study (see Shafer, et al., 2004).

Participants

Thirty-one children with typical language development (TLD) and 22 children with language impairment (LI) participated in these studies. Of the 22 LI children 14 of these could be characterized as having specific language impairment (SLI). To be included as TLD a child needed to be performing at grade level (as reported by the parent) show normal-range scores on tests of verbal and non-verbal ability, and to have age-appropriate language abilities, as assessed by a speech language pathologist (SLP). To be included as SLI, a child needed to be identified as SLI by an SLP, and perform poorly (<80) on at least two of the six subtests of the *Clinical Evaluation of Language Fundamentals 3* (3rd ed) (CELF 3) (Semel, Wiig, & Secord, 1995) in relation to the standardized norms (100). In comparison to our TLD group, the children characterized as SLI performed more than 1.5 SD below the TLD mean on the receptive and/or expressive CELF measure (< 96 and 90, respectively). Of the 22 children with language impairment, 14 performed within 1 SD of the standardized mean of 100 on the test of nonverbal intelligence (TONI) (in these studies, TONI > 85). An additional four LI children showed all other characteristics of SLI, but had somewhat lower TONI scores ranging between 75 and 81. Four children in our TLD group also scored rather low on the TONI with scores ranging between 75 and 83. Supplementary Tables S1 and S2 provide ages and test scores for each of the children for each study. These children are retained in the sample as IQ matches for the low IQ LI children, and their ERP measures in relation to IQ will be considered in the results. None of these children had any indication of

other known disorders or neurological causes. Four other LI children had additional issues meriting exclusion from the SLI or TLD group. These included one child who also had a fluctuating mild-to-moderate hearing loss (ID 62), one who had evidence of an attention deficit (ID 16 was reported to be on Ritalin, and could not complete the TONI) and one who had a performance IQ less than 70 (ID 19). A fourth child (ID 116) had low performance and low verbal IQs and the SLP suspected some language impairment, although the child did not quite reach the criteria for SLI. Tables 1 and 2 show the breakdown of TLD and LI children in terms of study, gender, age and mean (SD) test scores..

Stimuli and Procedures for all Studies

Table 3 presents an overview of the four studies. Greater detail can be found in Shafer, et al., (2000) for the Determiner (DET) study, Shafer, et al. (2005;2007) for the Short Vowel (SV) Study, Shafer, et al., (2007) and Datta, et al., (2010) for the Long Vowel (LV) Study, and Shafer, et al. (2004) for the Content Word (CW) Study. The stimuli on which the T-complex measures are performed are in the first row of Table 3 and bolded in the examples. The Stimulus characteristics and procedures are given in rows 3 through 12. Other stimuli and tasks in these studies are described in the last 5 rows. A brief description of each Study is presented below.

Stimuli and Procedures for the DET Study—A female native speaker of English recorded a children's story and a set of five nonsense syllables (ki, ko, po, gu, bu) that were used to construct meaningless sequences of syllables for a Nonsense condition. The same 75-ms exemplar of the function word "the" was spliced into two conditions (Story, Nonsense) and, in a third condition, repeated at a rate of one per 700 ms (Repetition). The Repetition task also included other function words, such as "a" "in a", that had been cut from the original text, but 69% of these words were "the". Subjects were presented with the three conditions (Story, Nonsense, Repetition) over ear insert phones. Children were asked to report what sounds they heard in the Repetition condition to focus their attention on the stimuli. Table 3 provides further details of the study. For all three conditions, ERPs were time-locked to the exemplar "the", which occurred at the onset of sentences for the Story and Nonsense Conditions.

The T-complex components of the ERPs to "the" in the Repetition condition are the dependent measures for the DET study in this paper. We chose not to measure the T-complex to "the" in the Story and Nonsense conditions because the determiner in these contexts was followed by speech 40 ms after its offset, which results in overlapping obligatory components and makes the measurement of the T-complex more difficult here. Also, the Repetition condition, although having fewer trials (100), was more similar in design to the SV and LV tasks. Supplementary Figure S1 displays Grand Mean ERPs to "the" in the Repetition condition at all 32 sites.

Stimuli and Procedures for SV and LV studies

For the SV (Short Vowel) and LV (Long Vowel) studies, a nine-step continuum of 250-ms, phonetically similar vowels was created from resynthesized natural tokens of a female speaker. For the SV study, 50-ms versions were cut from the center of these vowels and edited to a 5 ms rise and fall time. The LV study used the longer, 250-ms version (with 5 ms rise and fall times) of these vowels. The children in these experiments were presented with two tokens from the continuum in the ERP paradigm (see Table 3). One was perceived by adults as the vowel /I/ in 'bid', and the second was heard as [E] in "bet".

The studies shared identical designs, with the only difference being the stimulus duration. The two stimuli were presented in an oddball paradigm with /I/ occurring on 21% of trials

and /E/ on 79% of trials. Children received two tasks, one in which they ignored the stimuli and attended to a video with the sound muted (Passive), followed by a second condition in which they attended to target tones inserted randomly among the stimuli (Attend). The goal of the Attend/Passive Task manipulation was to determine whether attention would lead to a more robust MMN. Participants also performed three behavioral discrimination tasks and one identification task with these vowel stimuli. Details of these tasks can be found in Shafer, et al. (2005; 2007) and Datta et al. (2010).

The averaged ERPs to the standard stimulus were the focus of the current T-complex analysis because they provide excellent signal/noise. Supplementary Figures S2, S3, S4 and S5 display Grand Mean ERPs to the standard stimulus for the 32 sites for the SV Passive, SV Attend, LV Passive and LV Attend conditions, respectively.

Stimuli and Procedures for CW Study

Sixty-four pairs of CVC words and nonwords that differed by one phoneme (minimal pairs) in either the onset or final consonant were recorded. The word pairs were edited by splicing the consonant (and a portion of the adjacent vowel) from one recorded word onto another word (e.g., “p” from “pell” spliced onto “ell” from “bell. Identity Pairs (IP) of words consisted of the same nonsense word (pell-pell) or real word (bell-bell). Different pairs differed in the onset (e.g., pell-gell), or in the coda (five-fize). The edit point was never earlier than 100 ms into the vowel. Thus, acoustic-phonetic information to distinguish onsets was available at least 100 ms earlier than for codas. For example, the mean vowel durations for pairs differing in coda voice onset time was 167 ms for voiceless codas and 264 for voiced coda (eg., “date” vs. “dade”). The coarticulation cue to voiced consonants of increased vowel duration was not available until later than 167 ms. Each minimal pair was presented in both orders (Nonsense-Real and Real-Nonsense (see Shafer, et al., 2004 for the full stimulus details). Participants pressed one button following the second word (W2) of a pair if it was the same as, and a second button if it differed from the first word (W1).

The T-complex measured from the average ERP of the first word of pairs served as the dependent measure in this study. The second word of a pair was not included in this analysis because of possible confounds introduced by the same/different task. Supplementary Figures S6 and S7 display Grand Mean ERPs to The Real and Nonsense Words, respectively, across all 32 sites.

ERP Recordings and Analysis

For all studies, the electroencephalogram (EEG) was sampled at 512 Hz, bandwidth of 0.05–100 Hz, from 31 scalp sites referenced to the nose. An electrode placed 1 cm below the left eye and referenced to FP1 was used to monitor eye movement. The epochs of the EEG time-locked to the onset of the stimuli were averaged and digitally filtered (low-pass 30 Hz). Epochs with artifact greater than $\pm 100 \mu\text{V}$ were not included in the averaged response. All stimuli were baseline corrected after averaging. The DET and CW studies used a 100 ms prestimulus baseline and the SV and LV studies used a 50 ms prestimulus baseline. For the SV and LV study, participants had a minimum of 545 trials per condition (see Shafer, et al, 2007). For the CW study, children had at least 70 trials per condition (out of a total of 128), and for the DET study, 54 (out of a total of 100 trials) No significant differences in number of trials were found between the TLD and LI groups for any study ($p > 0.1$).

Analyses

The T-complex measures were made relative to the pre-stimulus baseline. The peak amplitude and latency of the Na, Ta and Tb peaks were identified at sites T7 and T8. The right Ta peak was easily identifiable in most individuals' waveforms (89% of 144 cases

across all experiments and conditions) and was selected as the most positive-going peak between 95 and 150 ms. Eleven percent of the cases had no clear peak in this range, and expanding the range from 88 to 160 ms, led to identification of 12 more peaks. For the remaining five cases, a point of change in slope (elbow) in the narrower range was selected. For the T7 Ta, 75% of the cases were easily identifiable peaks in the narrower range. Using the wider range, fifteen additional peaks were found. For the remaining 21 cases, an elbow within the narrower range was selected. Na was selected as a negative-going deflecting in the latency range of 60 to 95 ms. For T8 Na, 89% were clearly identifiable in this range. Expanding the range from 45 to 115 ms allowed identification of eleven cases. For five remaining cases an “elbow” within the narrower range was selected. For Na T7, 80% were clearly identifiable within the narrower range. Using the wider range identified 16 more peaks. Two Na peaks were found very late (130 ms). The remaining 11 peaks were elbows in the narrower range. For T8 Tb, a clear negative-going peak was found between 130 and 200 ms for 76% of the cases. Expanding the window to 225 ms allowed for identification of 3 more peaks. For the remaining 31 peaks an elbow in the narrower range was selected. For T7, Tb was a clear peak in the narrower range for 71% of the cases. Expanding the range to 225 ms allowed for the identification of three more peaks. An additional 43 cases were identified as an elbow in the narrower range. Six cases had no peak or elbow between 130 and 225 ms, following the Ta peak. In these cases peaks were found between 230 and 281 ms. Amplitudes for Na and Tb were calculated as differences from Ta because these differences could represent the absence of clear peaks that was found in 25 to 30% of the cases, and reveal whether one group had a more prominent Na, or Tb relative to the Ta than the other.

Root mean square amplitude (RMS, the square root of the mean of the squares of each amplitude point) for T7 and T8 was calculated from 50 to 200 ms for each child in each condition and study to examine the magnitude of the T-complex.

To examine waveform morphology similarities, a grand mean waveform for each condition in each study was calculated from the TLD data to serve as a template. Each child's waveform for a particular condition was correlated using Pearson's Product Moment Correlation (Priestley, 1992, Equation 2.12.51) to the TD grand mean template within the 50–200 ms interval (78 time points) to reveal whether a child's waveform shows the same shape as the TLD grand mean waveform, irrespective of absolute differences in amplitude. The 95% confidence intervals are reported where relevant.

For each study, the amplitude measures were transformed into z-scores using the means and SD of the TLD group. Mean z-scores and correlation values at T7 and T8 were calculated for each child (averaging across conditions and studies). Sensitivity and specificity were calculated using these mean z-scores and correlations, and 95% confidence intervals are reported for these statistics. Sensitivity is calculated as $TP/(TP + FN)$ and specificity by $TN/(TN + FP)$ where TP = true positive, FN = false negative, TN = true negative and FP = false positive. The Fisher Exact Test (similar to Chi Square, but for small groups) was used to test whether there were significant group differences above and below the medians for the z-transformed amplitude and the waveform correlation measures. Spearmann's rank order correlation was used to examine the relationship between amplitude z-scores and waveform correlation measures.

Results

Figures 1–4 compare the Grand Mean ERPs at T7 and T8 for the TLD and LI groups in the four studies (the four LI children, ID16, ID62, ID19 and ID116 are not included in the grand means, and the t-test comparisons in this section because they have additional factors, such

as hearing loss, that justified exclusion from this set of the comparisons). The left site T7 is shown on the left, and the right site T8 on the right. What is immediately apparent is that the Ta peak is more prominent and positive in amplitude for the TLD than the LI groups. Only for the left site in the Long Vowel study does this generalization not hold (see Figure 3). In this case, the waveform is more negative in amplitude for the TLD than the LI group, although the peaks are still more prominent for the TLD than LI children. As a first pass analysis, t-tests were used to determine whether there were significant differences between groups in the latency of the Na, Ta or Tb and in the amplitude of the Ta peak, as measured from the baseline and from Na (Na-Ta) and from Tb (Ta-Tb). These latter two measures examine whether it is the prominence of the peak, rather than the absolute amplitude that is important. Table 4 reveals that for latency, out of the 42 comparisons, only six showed a p-value less than 0.1 (one-tailed), and for three of these comparisons, the LI children had earlier peak latencies than the TLD children (SV Passive and Attend left Tb peak and Passive left Ta peak). However, after removing two outliers from the TLD group in the Short Vowel Study who had very late Tb peaks (> 250 ms), the latency difference is no longer significant. For the remaining three significant tests, the TLD had shorter latencies (right LV Ta and CW Nonsense Na and Ta). With a p-value set at 0.1, one would expect approximately 4 false positives from 42 comparisons. This outcome suggests that the latencies of Na, Ta and Tb were generally comparable for the two groups.

The waveform correlations between the individual participants and the TLD mean reveal a general pattern of lower mean correlation for the LI children than the TLD children across all conditions in all four studies, as shown in Table 5. Confidence intervals at the 95th percentile for a $r = 0.23$ (78 timepoints) ranged from 0.008 to 0.43 (and from -0.008 to -0.43 for a $r = -0.23$). Thus, any correlation between ± 0.23 is not significantly different from 0. Examination of the correlation SDs indicates a great deal of variability within groups. The t-tests comparing the groups showed significantly lower waveform correlation values for the LI compared to the TLD children in the Long Vowel Study for all but the Passive condition left (T7) site. The children with LI also tended to show significantly poorer correlation values for the Real Word left (T7) and Nonsense Word right (T8) site, in the CW Study. The SV and DET studies showed no differences. These results suggest some difference in waveform morphology across groups but not independent of the specific studies.

In comparing peak amplitudes, the LI group had lower amplitude Ta in all but two measures (left site LV passive and attend), and generally smaller peak-to-peak Na-Ta and Ta-Tb across studies and conditions (see Table 6). These differences were significant (one-tailed, $p < 0.05$) for Ta amplitude at the right site for all but the SV Attend condition. The peak-to-peak measures showed a similar pattern for the right site. The left site Ta amplitude showed significant group differences for the DET, CW Real, SV Attend and Passive conditions. The peak-to-peak measures, rather than Ta amplitude alone, showed significant group differences for the LV Attend condition at T7. The amplitudes for the LV attend condition measured from the baseline to the Na and Tb peaks were more negative by about $1.50 \mu\text{V}$ and to the Ta peak by about $0.50 \mu\text{V}$ for the TLD children compared to the LI. So despite greater negativity across this interval for the TLD group, they had a more prominent Ta peak than the LI group. The LV Passive condition shows a somewhat similar pattern with eight of the 11 TLD children but only 4 of the 9 LI children showing the Ta-Tb measure greater than $1 \mu\text{V}$.

The RMS measure showed significant differences only for the Real Word condition of the CW study at the right site, but the measure approached significance for the Long Vowel left site and left and right sites in the Nonsense Word condition of the CW Study (see Table 7).

In summary, these comparisons suggest that the amplitude of Ta measured from the prestimulus baseline best captures the group differences regardless of study. Only the LV Study was different, in that the peak-to-peak measures for the left site rather than Ta amplitude showed significant differences. The waveform correlation measures showed significant group differences for two of the four studies, the LV Study and the CW Study.

Collapsing across studies

The amplitude data were transformed to z-scores using the mean and SD of the TLD group from each study as the template. Figure 5 shows the distribution of individual scores (amplitude on the y axis). Four of the children (ID 16, ID 19, ID 62, ID116) who had additional issues, as described above, were excluded from the following comparisons. For the right site Ta measure, four of the 18 language impaired children had z-scores above -0.5 standard deviations (31st ranked value) from the mean. In contrast, 25 of the 31 children with TLD had z-scores above this value, giving a sensitivity of 0.83 (95% confidence interval (CI) 0.59 to 0.96) and specificity of 0.81 (CI = 0.63 to 0.93) (Fisher-Exact, $p = 0.0001$). We also examined children included under the stricter classification for SLI (nonverbal IQs > 84). When examining the 14 SLI children compared to the 27 TLD children (with nonverbal IQs > 84), two of the 14 children with SLI and 23 of the 27 children with TLD showed z-scores above -0.5 (27th rank, after excluding low nonverbal IQ children), resulting in higher sensitivity and specificity values (0.86 (CI = 0.57 to 0.98) and 0.85 (CI = 0.66 – 0.96), respectively). For the left Ta measure, ten children with LI fell above -0.5 (31st ranked value) and eight below this value, while 20 of the children with TLD fell above and 11 below this value. Sensitivity was 0.65 (CI = 0.45 to 0.81) and Specificity 0.44 (CI = .22 to .69) (Fisher Exact, $p = 0.56$). The sensitivity and specificity still remained poor when examining the children with non-verbal IQs above 84. Eight of the 14 children with SLI compared to 18 of the 27 with TLD showed z-scores above -0.55 (27th rank), revealing a sensitivity of 0.69 (CI = 0.48 to 0.86) and specificity of 0.40 (CI = 0.16 to 0.68) (Fisher exact, $p = 0.73$). Interestingly, at this left site the Na-Ta measure is more sensitive than absolute amplitude of Ta. No LI child had a z-score above 0 (and 16 children with TLD did). The sensitivity using a z score of 0 as the cutoff, thus is 1 (CI = 0.85–1), but specificity is lower at 0.52 (CI = 0.33 to 0.70) (Fisher Exact, $p = 0.0001$). In comparing the 14 SLI children to the 27 TLD children (with normal IQ), we show slightly higher specificity (0.59), because the 4-low IQ TLD children all had negative z-scores. In sum, a child with a left Na-Ta peak above the TLD mean was never a child with SLI or LI.

In examining the waveform correlation measures (using the mean correlation value for a child participating in more than one study), for the right site, five of 18 children with LI and 22 (of 31) with TLD had correlation values greater than the value of 0.51 (CI = 0.32 to 0.66). Sensitivity was 0.71 (CI = 0.52 to 0.86) and Specificity 0.72 (CI= 0.47 to 0.9) (Fisher Exact, $p = 0.007$). Examining the 14 children with SLI compared to the 27 TLD controls (with normal non-verbal IQ), using the 0.51 value, revealed a sensitivity of 0.70 (CI = 0.50 to 0.86) and specificity of 0.78 (CI = 0.49 to 0.95) (Fisher exact, $p = 0.007$). For the left site, five children with LI (of 18) and 21 (of 31) with TLD showed correlation values above the value of 0.31 (CI = 0.09 to 0.50), leading to a sensitivity of 0.72 (CI = 0.47 – 0.90) and Specificity of 0.68 (CI = 0.49 – 0.83) (Fisher Exact, $p = 0.009$). Sensitivity and specificity for the 14 SLI and 27 TLD children was 0.79 (CI = 0.49 to 0.95) and 0.70 (CI = 0.50 – 0.86), respectively, with four of the SLI and 17 of the TLD group showing correlation values above 0.31.

Including all children, Ta amplitude and the waveform morphology correlation values were significantly correlated, particularly for T8 (T7, $r = 0.39$ [CI = .13 – .60], $p = 0.004$; T8, $r = 0.69$ [CI 0.51 – 0.81], $p = 0.0001$). Figure 5 illustrates that, generally, children with higher amplitude Ta measures also had higher waveform correlation values.

Measures across studies

Ta amplitude (in terms of z-scores) was highly correlated across conditions at the right site for all experiments and the left for two of the three experiments that had two conditions (Attend vs. Passive: SV, $p = .0001$; right: $r = 0.92$, CI = 0.85 – 0.97; left: $r = 0.87$, CI = 0.73 – 0.94; LV, $p < 0.0004$; right: $r = 0.72$, CI = 0.40 – 0.88; left: $r = 0.71$, CI = 0.38 – 0.88; Real vs. Nonsense CW right: $r = 0.54$, CI = 0.37 – 0.82; $p = 0.038$; left: $r = 0.22$, CI = –0.33 – 0.66; $p = 0.43$). The relatively lower correlations for the CW study are due to two outliers (ID 29 for the right and ID 29 and ID XA for the left). ID 29 was a child with typical language who had low z-scores for the right and left Nonsense Word conditions (–1.92; –1.82, respectively) but better scores for the Real Word condition (0.27; 0.01, respectively). ID XA also had better z-scores for the Real Word than the Nonsense Word conditions for the left site (NW = –0.48 RW = 1.67). The correlation jumps up to $r = 0.72$ (right, $p < 0.004$) and $r = 0.52$ (left, $p = 0.07$) after removing these outliers. Note that ID 29 was one of the three children with TLD who showed very poor Ta amplitude averaged across studies.

The correlation between conditions of the same study for the waveform morphology values (in terms of correlation of each child's waveform to the TLD mean template) were also high at the right site ($p < 0.0001$, right SV attend vs. passive: $r = 0.92$, CI = 0.84 – 0.96, $p < 0.0001$; right LV attend vs. passive: $r = 0.94$, CI = 0.85 – 0.98; right CW NW vs. RW: $r = 0.53$, CI = 0.03 – 0.82, $p = 0.04$). Removing one outlier from the CW study (ID126) raised the correlation to $r = 0.68$. The left site showed significant correlations only for the Attend and Passive conditions in the SV and LV studies, (left SV Attend vs. Passive: $r = 0.91$, CI = 0.81 – 0.96, $p < 0.0001$; left LV Attend vs. Passive: $r = 0.47$, CI = 0.04 – 0.76, $p = 0.035$), but not for the left site across the NW and RW conditions of the CW study ($r = -0.37$, CI = –0.75 – 0.17, $p = 0.17$).

In summary, conditions within the same experiment showed very high correlations in amplitude, at the right site, and fairly good correlation at the left site. The waveform morphology measures were also highly correlated for the right and left sites in the SV and LV conditions, but more weakly correlated for the Nonsense Word and Real Word conditions at the right site and not at all for these conditions at the left site in the CW study. The lack of a correlation here suggests that left temporal site timing may be mediated by lexical factors. Specifically, children with typical language generally showed good left temporal measures to the Real Word condition, whether they showed poor or good measures to the Nonsense Word condition.

Across experiments, the nine participants in the LV and SV studies show Ta amplitude correlations that are significant or approaching significance for all but the left Attend conditions (right: Attend LV vs. SV, $r = 0.81$, CI = 0.32 to 0.95, $p = 0.008$; Passive LV vs. SV $r = 0.64$; CI = –0.05 to 0.91, $p = 0.066$; left: Attend LV vs. SV, $r = -0.09$, CI = –0.71 to 0.61, $p = 0.82$; Passive LV vs. SV $r = 0.83$; CI = 0.51 to 0.95, $p = 0.0004$). The 13 participants in both the SV and DET studies showed significant correlations for the right, but not left Ta measures (right: average of Attend SV and Passive SV vs. DET $r = 0.56$, CI = 0.016 – 0.85, $p = 0.046$; left: $r = 0.23$, CI = –0.37 to 0.69, $p = 0.45$).

Likewise, the right waveform morphology measures were significantly correlated across experiments (SV vs. LV, Attend: $r = 0.80$, CI = 0.29 to 0.96, $p = 0.01$; Passive: $r = 0.89$, CI = 0.54 to 0.98, $p = 0.001$) or approached significance (DET vs. SV: $r = 0.49$, CI = –0.01 to 0.82, $p = 0.09$). Removal of one outlier (ID116) from the DET vs. SV comparison raises the correlation to $r = 0.62$, $p = 0.03$. The left waveform morphology measures did not show significant correlation across studies (SV vs. LV, Attend: $r = 0.36$, CI = –0.40 to 0.83; $p = 0.34$, but removal of one outlier leads to: $r = 0.70$, $p = .051$; Passive: $r = 0.04$, CI = –0.64 to 0.68, $p = 0.92$; DET vs. SV: $r = 0.19$, CI = –0.40 to 0.67, $p = 0.54$).

The number of participants in the DET and LV studies (eight) or in both the CW and other studies (LV, SV, or DET) were too few (five, at most) for any confidence in correlation measures, and thus, they are not examined here.

In summary, the right site amplitude and waveform morphology measures showed fair to high correlations across studies. The left site measures generally showed no or weak correlation across studies. This finding suggests that the T-complex at the left site is more influenced by stimulus or task than at the right site.

Relationship between T-complex and other measures of processing and language

Our previous analyses have demonstrated that a larger number of children with LI (and more narrowly, SLI) have poor Ta amplitude and T-complex morphology than would be expected by chance, particularly at the right temporal site. It was also the case that the LI children had poor neurophysiology for other measures, as demonstrated in previous reports. Below, we examined how the T-complex measures relate to these other neurophysiological measures. The principal question addressed here is whether the T-complex corresponds more closely with some than other neurophysiological measures of speech and language processing. Finding a strong relationship between measures will suggest that the processes being indexed may be connected with one feeding into the other.

T-complex and MMN—In our previous investigations examining automatic discrimination of vowel sounds, significant differences in the MMN measure between children with TLD and SLI were only found for the short vowels (SV) and not the long vowels (LV). Specifically, in the SV study (Shafer, et al., 2005), only two of eight children with SLI showed robust MMNs in one of the two conditions (Attend or Passive), whereas 8 of 11 children with TLD showed robust MMNs in both conditions. Robust MMNs were defined as negativity greater than $-1 \mu\text{V}$ of the difference wave averaged across all frontocentral sites (F3, FZ, F4, C3, CZ, and C4, re-referenced to the mastoids because these sites are expected to show opposite polarity) between 190 and 270 ms. Approximately half of the SLI children in both the SV and LV studies also showed poor categorization of the stimuli into the two vowel categories [I] versus [E], whereas all of the children with TLD showed good categorization. In this section, we examine whether there is any relationship between the MMN in the SV study and the T-complex measures.

In the data analyzed for the current study, five additional TLD children were included in the SV study and the majority of these children with TLD showed robust MMNs (16 of 17 children in at least one of the conditions, and 11 of 17 in both the Attend and Passive conditions). All children above the 17th rank (the number of TLD children in the study) showed negativities ranging from -1 to $-4.6 \mu\text{V}$ and those below the 17th rank, values ranging from -0.5 to $1.5 \mu\text{V}$.

Poor T-complex measures are defined as falling below the 17th rank. Four of the 17 TLD children fell below the 17th ranked score for Ta amplitude ($z < -0.40$) in this study (but one at rank 18: ID 40) and five for waveform morphology (see Tables 8 and 9). The one child (ID74) showing both poor Ta amplitude ($z < -0.91$) and morphology ($z < 0.38$) also showed no clear MMN in the Passive or Attend condition for the SV study (and also showed no MMNs for the LV study). The other TLD children with a poor T-complex measures, however, showed robust MMNs in one or both conditions.

With regards to the children with LI, of the 11 participating in the SV study (8 of whom formed the SLI group in Shafer, et al., 2005), three showed robust MMN in at least one of the conditions (Attend or Passive; see Tables 8 and 9). For these three children the T-complex measures fell below the 17th rank for the right Ta amplitude and waveform

morphology. All three of these participants showed poor categorization of the short vowels into the two categories /I/ vs. /E/. Only two LI children fell above the 17th rank for both right Ta amplitude and T-complex waveform morphology. One other LI child showed Ta amplitude and two others showed waveform morphology above the 17th rank. All five of these children showed poor MMN (values between 0.9 μ V and -0.4 μ V) although two of these (ID 17 and ID 38) showed good categorization of the short vowels.

Thirteen of the 17 children (76%) from the TLD group had both good T-complex measures and a robust MMN in at least one of the two SV conditions, but none of the children from the LI group showed this pattern. In contrast, six of the 11 children (55%) from the LI group showed both poor T-complex measures and poor MMN in both conditions. Only one child from the TLD group did not show an MMN in any condition of the SV (or LV) study and also showed poor T-complex measures. Our results also show that it is possible to have robust MMN and poor T-complex measures, as found in the case of three children with TLD and three children with LI. The children with LI also showed two cases of robust T-complex measures, but poor MMN measures.

T-complex and P100—A number of children with SLI also showed delayed P100 peak latencies to the long vowels of the LV study (Shafer, et al., 2007). We suggested that this late peak might indicate slower processing, or alternatively, might be a consequence of the children with SLI showing less attentional shift to the vowels. Attentional shifts were seen as increased negativity (the Nd component) at frontal central sites when attending to the auditory modality compared to the visual modality (Shafer, et al., 2007). Increased negativity could overlap with the P100 peak to result in an earlier peak in the children with TLD.

Three of the ten children with TLD showed late P100 peaks (> 7 ms or 1 SD) from the TLD mean of 90 ms for either the Attend or Passive condition, but only one for both conditions. Four of the ten TLD children showed below median right T-complex measures for either Ta amplitude or T-complex morphology, but of these, only ID 74, who showed poor T-complex amplitude, also showed late P100. (see Tables 8 and 9).

For the LI children, five of the ten showed late P100 latencies for either or both (four for both) the LV Passive and Attend conditions and poor T-complex measures (see Tables 8 and 9). For the five who showed P100 latencies within the 1 SD range of the TLD mean, four fell below and one at the median for right Ta amplitude and three for waveform morphology ($r < 0.69$). Only one LI child (ID 101) showed fairly good T-complex and P100 measures, but she performed poorly on categorizing the vowels in the behavioral task, similar to many of the other children with SLI.

Looking across studies, 11 of the 20 showed either both good or both poor measures (i.e., T-complex and P100). Only one of the 10 TLD group showed both late P100 and poor T-complex measures, and five (50%) of them showed good scores for all these measures. In contrast, only one of the 10 children in the LI group showed both normal-range P100 latencies and at or above-median T-complex measures. Five (50%) of the children with LI showed both late P100 and poor right T-complex measures.

T-complex and ERP measures of sentence-processing in discourse (DET study)—In Shafer, et al. (2000) we found that children with SLI showed reduced amplitudes between 200–400 ms at left temporal sites, and increased amplitude at the right temporal site time-locked to the determiner “the” at the onset of sentences in a story. In addition, many of the children with SLI showed less vertex positivity during the story condition. Both the children with SLI and TLD showed evidence of differentiating the

meaningful story sentences from the nonsense, with positive amplitudes at lateral anterior sites to “the” in the story, but falling to zero for “the” followed by nonsense syllables. We interpreted the increased right, and reduced left temporal positivities (TPs) as indicating that children with SLI were making less use of linguistic properties (e.g., morphosyntax) and more use of discourse strategies to comprehend the story (also see Shafer, et al., 2005). The absence of the vertex positivity was less clear; however, calculating scalp current density attenuates this vertex positivity from the TLD data, suggesting that it has contributions from deep cortical sources, such as the hippocampus or basal ganglia structures (Shafer, et al., 2000).

Of the twelve children with TLD in the current study, nine showed large left TPs ($> 5 \mu\text{V}$) and seven showed left-greater-than-right (L>R) TP asymmetry in processing “the” in the story condition. Ten of the 12 TLD participants showed vertex positivity greater than $3 \mu\text{V}$ between 200 and 400 ms to “the” in the stories. For the T-complex measures to the determiner in isolation, only one of the 12 TLD participants showed both right Ta amplitude and T-complex morphology below the 12th rank. This child’s other measures, however, were consonant with the typical group patterns (L>R TP amplitude and robust vertex positivity). Two other children from the TLD group showed right Ta-amplitude below the 12th rank, but good T-complex morphology. These two children both showed the LI pattern of R>L TPs to the determiner in the story condition, but one showed fairly large left TP ($6 \mu\text{V}$) and both also showed robust vertex positivity. Both of the TLD children with poor vertex positivity showed robust right T-complex measures ($> 12^{\text{th}}$ rank) and robust left TP, although one also showed R>L TP (see Tables 8 and 9).

Of the LI children, seven of the nine showed two or more poor measures (see Tables 8 and 9). Four showed small left TPs ($< 5 \mu\text{V}$), and six showed reversed right-greater-than-left (R>L) asymmetry. Six of the nine children with LI also showed poor vertex positivity. Only two of the LI children fell above the 12th rank for the right Ta amplitude and T-complex waveform morphology. For one of these (ID65), all other measures in the DET study were poor. The other child (ID 47) was the only LI child to show robust scores for all the DET measures.

Looking across all the children, five of the 12 children with TLD but only one of the nine with LI showed good scores across all measures in the DET study. Eight of the nine children showing L>R TP asymmetry also showed T-complex measures above the 12th rank, although the reverse R>L asymmetry was found for four children (one LI) showing good T-complex measures. Thirteen of the 21 children from both groups showed comparable vertex positivity and T-complex (either both good or both poor). The principal difference between the children with TLD and those with LI is that children with LI have more poor measures (typically two or more) than those with TLD.

T-complex and measures of lexical discrimination—The CW study examined SLI versus TLD children’s discrimination of CVC word pairs in a match-to-sample task where children were asked to press one button for same pairs and a second button for different pairs. Most of the children with TLD showed a posterior negativity (N400), largest over lateral sites P7 and P8, in conjunction with a slow posterior positivity, largest near Pz (Pz-pos). The N400 peak latency ranged between 240 and 395 ms for pairs differing in the onset consonants and 450 and 600 ms for pairs differing in the coda for children in the TLD group. The children with SLI significantly differed from the TLD group in that fewer showed robust Pz-pos. Many of the SLI children also showed later (or absent) N400 responses (Shafer, et al., 2004).

One additional group difference in the ERP data that was not examined in Shafer et al. (2004) needs to be addressed here because it may partially overlap with the T-complex measures. At the right site (T8), children from the TLD group showed significantly greater amplitude for a positivity peaking at approximately 380 ms (P380) than those with LI (RW, $t = 3.4$, d.f. = 13, $p = 0.004$; NW, $t = 3.03$; d.f. = 13, $p = 0.01$). All eight children with TLD exhibited positive peaks between 350 and 400 ms, and for seven of the eight children the P380 was greater than 3 μ V. For the seven children with LI, the P380 peak was less than 3 μ V for five of them, and actually below the baseline (i.e., negative relative to the prestimulus baseline) for one or both conditions for these five LI children. As shown in Figure 6, this positivity may be overlapping with the T-complex peaks and lead to more positive values for the Ta measure in the TLD group. For this reason, we will also make use of the Na-Ta measure, which is minimally affected by any overlap with the onset of the P380 peak.

The two groups also showed a significant difference in behavioral response RTs (Shafer, et al. 2004). Children with SLI were considerably faster (by > 83 ms) at making a decision for words that differed in the first consonant (onset) compared to final consonant (coda), for the Nonse-Real order, whereas children with TLD showed less difference (< 83 ms). An adult control group showed the same pattern as the TLD children (Shafer, et al., 2003). Delaying the response to the end of a word, whether the word pairs differed in onsets or codas, suggested that the children with TLD were making use of lexical information. In contrast, faster responses to onset than codas, as found for many of the children with SLI, suggested a strategy relying on phonetic/phonological rather than lexical information. Recall that the information that stimuli differed in the coda was never available until at least 100 ms later than for differences in the onset consonant.

For the TLD children in the current report, seven of the eight (88%) showed robust Pz-pos (> 10 μ V) to words differing in the onset consonant and five of the eight for words differing in the coda (averaged across Nonse-Real and Real-Nonse orders) (see Tables 8 and 9). Seven of the eight TLD children also showed N400 latencies within 1 SD of the TLD mean. With regards to the T-complex measures, six of the eight (75%) children with TLD showed right T-complex morphology at or above the 8th rank, and seven of the eight for right Ta amplitude. Interestingly, all of the children in the TLD group showed higher right Ta amplitude z-scores than the children in the LI group for the RW condition. One child in the TLD group (ID 29) showed multiple poor measures. The only robust neurophysiological measures for this child were the T-complex measures to real words. However, this child showed the typical response pattern in the match-to-sample task as the other children from the TLD group.

For the LI children, only one child showed robust Pz-pos (> 10 μ V) for either the onset or coda differences. Furthermore only two of the LI children had an N400 peak latency to pairs differing in the onset ranked in the top eight. There was more overlap in the peak N400 latency for the coda differences for the two groups, but two of the LI children showed no evidence of N400 for at least one coda condition. Three of the LI children (ID 38, ID 54 and ID 59) showed a response pattern for the Nonse-Real coda pairs that was similar to the TLD group (i.e., RT difference < 83 ms), but of these, only ID 59 showed the Pz-pos.

With regards to the T-complex measures, no LI child fell above the 9th rank for both the right Ta amplitude and T-complex morphology. For the right Ta amplitude measures, all of the LI children fell below the 7th rank. When using the right Na-Ta amplitude only one child falls above the 8th rank (ID 44).

Looking across children from both groups, the T-complex measures and the Pz-pos neurophysiological index of word discrimination were both good or both poor in most cases (11/15; 73%). For the N400 measure, T-complex was comparable in 12 of 15 children (80%). Five of the eight children (64%) from the TLD group, but none from the SLI group showed good scores for all measures. Only one child from the TLD group showed more than two poor measures (see Tables 8 and 9). In contrast all seven of the children with LI showed three or more poor measures.

Summary across experiments: These comparisons across studies reveal a different pattern for children from the TLD group compared to those from the LI group. Few children with TLD showed more than one poor neurophysiological measure for a given study. Of the 31 children from the TLD group, 15 (48%) had good measures for all experimental tasks (and none for the LI group, Fisher Exact, $p < 0.01$). Only three of these 31 (1%) children showed poor right T-complex amplitude and morphology (in one or more of the experiments each participated in) and at least one additional poor measure. The poorest neurophysiology for children in the TLD group was found for ID 29, ID 115, and ID 74 (see Tables 8 and 9). Of these, ID 29 and ID 115 were two of the three TLD children showing below median right Ta amplitude and T-complex morphology (lower right quadrant of Figure 5). (ID 118 was the third TLD child with below median measures, but all other measures were good.)

In contrast, 20 of the 22 (91%) children with LI showed two or more poor neurophysiological responses in a given study in contrast to 10 of 31 (32%) from the TLD group (Fisher Exact, $p < 0.01$). Fourteen of these LI children (64%) show three or more poor measures, as can be seen in Tables 8 and 9. Only ID 101, who participated in the LV study, showed no poor neurophysiological measures. However, her behavior (poor categorization of the vowels) and poor language scores indicate that she is SLI. The children who showed poor language (and were categorized as LI), but who were not strictly SLI showed poorer neurophysiology than those in the TLD group.

Discussion

These data confirm previous studies that suggest that poor auditory processing, and perhaps, specifically speech processing, is associated with LI. Many of the children with LI (and more narrowly, SLI) showed poor speech processing, as measured by right Ta amplitude and waveform morphology. The Ta amplitude measured from baseline and the T-complex waveform correlation measure best served to distinguish children with LI from those with TLD.

Our results also suggest that poor speech processing, as indexed by right T-complex measures, does not necessarily accompany LI and that there are some cases of LI where speech processing abilities seem normal. Specifically, a few children with TLD showed poor Ta amplitude and T-complex waveform morphology measures, but good language, suggesting that, if poor T-complex measures indicate poor speech processing as some level, then there are ways of compensating for the poor speech processing that results in good language abilities; furthermore, a few children with LI showed good T-complex measures, supporting the claim that poor language can result from factors other than poor speech processing, as indexed by the T-complex measures. Alternatively, poor speech processing abilities during early development may have resolved by the age at which we tested the children. Even with these exceptions, roughly 75% of the children with LI showed poor Ta amplitude and waveform morphology at the temporal sites, most clearly seen on the right, suggesting that the speech processing function at the level indexed by the T-complex plays an important role in language development and/or language processing. These findings,

however, do not indicate the directionality of the relationship. Poor language learning, itself, could lead to poor function of the cortex indexed by the T-complex measures.

The data also reveal that children with LI show poor neurophysiological and behavioral processing on multiple levels. That is, many of the children with LI showed deviant, late or absent ERP measures of other levels of processing, such as encoding and discrimination (measured by the P100 and MMN), sentence/discourse processing, as measured by the TP and vertex positivity in the DET study, and lexical access as measured by the N400 and PZ-pos to words pairs in the CW study. In contrast, for cases where evidence of deviant right Ta amplitude and T-complex morphology were found for a child with TLD, most other measures generally yielded good or excellent scores. However, the relationship among the different measures was not simple. For example, even though poor T-complex measures generally were seen in conjunction with poor preattentive discrimination, as indexed by MMN, there were several exceptions among the children with TLD.

Below we discuss a number of explanations for the pattern of results we found across studies. First, we address the consistency of the T-complex findings across studies and then how the T-complex measures are related to other measures in the same and different experiments. In the final sections, we ask what speech processing function is indexed by the T-complex, and specifically, the Ta component, and how this function might be related to poor language development.

T-complex measures across studies

Even though the principal goal of this study was not to look across studies, it is useful to ask whether consistent differences in the TLD and SLI groups are found across conditions within and across studies. We can examine whether a child's T-complex data showed consistency, in terms of z-scores and correlation measures across conditions within the same study, or across studies, where possible. Excellent correlations of the amplitude and morphology were found across conditions within a study for the SV and LV experiments at both right and left sites. The correlation was weaker for the nonsense word and real word conditions in the CW study, and in particular there was no correlation between the left waveform morphology measures to nonsense words and real words. Across studies, fairly good correlations are found for the right site amplitude and waveform morphology measures, but less so for the left temporal site. Children with LI generally showed poorer Ta amplitude and T-complex morphology measures at both the left and right sites, regardless of stimulus or task type. However, the measures are more consistent at the right site. It is possible that the right temporal site T-complex is less influenced by stimulus and task factors than the measures at the left site. However, lexicality appears to affect the right T-complex measures in one case. All children with TLD exhibited better right Ta amplitude to the real words than any child with LI in the CW study. The Ta amplitude to the nonsense words, however, showed two children from the TLD group falling below the median value. The relatively early timing of the Ta component (around 115 ms) may at first seem to preclude lexical effects, but the children heard each word four times (twice and for two orders), which would allow them to develop lexical expectations (also see Hauk, Davis, Ford, Pulvermüller, Marslen-Wilson, 2006). It is also possible that the apparent lexical effect on the T-complex measures was, in fact, due to lexical effects on the following P380 measure. Several studies have shown that a temporal-site positivity, peaking around 350 ms in adults, is sensitive to the degree of phonological correspondence between a prime and target word (e.g., Freidrich, 2005; Friedrich, et al. 2009). This P350 in adults shows greater amplitude for words that differ compared to those that share phonemes (or prosody). The authors suggest that the P350 indexes "fine grained mapping of the input onto lexical representations" (Friedrich, et al. 2009). In the current study, the positivity peaks 30 ms later for children than adults, but its onset may overlap with the T-complex, leading to increased

positivity for the children with TLD, compared to those with SLI. Future studies will be needed to examine whether lexical knowledge truly influences the Ta amplitude and to what extent it correlates with the P350/P380 amplitude.

In summary, despite the large differences in stimuli and design across studies we observed the same general pattern of poor Ta amplitude and T-complex waveform correlation in children with LI and the smaller group with SLI. An interesting finding was that the TLD children all showed good Ta amplitude at the right site for the real words of the CW study, whether they showed good or poor measures for the other stimuli (i.e., nonsense words or speech stimuli in the other studies). These findings suggest that the T-complex components are additional measures of speech function that can be examined in ERP speech or language processing studies without the necessity of designing an additional lengthy condition to elicit these measures.

Relationship between T-complex and other neurophysiological measures

A question arising from these data is whether there is evidence that the processing indexed by the Ta amplitude and T-complex morphology is directly related to processing measured by other neurophysiological components, such as P100, MMN and N400. We had hypothesized that the T-complex measures were more likely to show strong relationships with measures such as the P100 and MMN because these components index levels of processing related to sound encoding and discrimination. Our findings, however, do not support this hypothesis. In fact, the neurophysiological measures of lexical discrimination in the CW study and sentence processing in discourse in the DET study seem to be more related to the T-complex measures. The MMN and P100 measures showed many more exceptions in their relationship with T-complex measures than N400 and Pz-pos in the CW study or TP asymmetry in the DET study. Specifically, for the 28 children participating in the SV study, 18 (64%) showed comparably good (or poor) right T-complex and MMN measures, but 10 showed contrasting measures (i.e., robust MMN, but poor T-complex or deviant MMN and robust T-complex). In the LV study, comparable P100 and T-complex measures were found for only 12 of the 20 participants (60%). In contrast, 16 of the 20 children (80%) in the DET study showed comparable T-complex and TP asymmetry. Of the nine children showing robust L>R TP in the DET story condition, seven (78%) showed good T-complex measures, although the opposite R>L TP did not always co-occur with poor T-complex measures; three of the 11 children (27%) showing R>L asymmetry also showed good T-complex measures. Only 13 of the 21 children (62%) showed comparable T-complex measures to “the” in the Repetition condition and vertex positivity to “the” in the Story condition. In the CW study, the Pz-pos showed comparable robustness to the T-complex measures for 10 of the 15 children (67%) and the N400 was comparable for 12 of the 15 children (80%).

These patterns suggest a stronger relationship between the processes indexed by the right T-complex measures and processes of lexical discrimination and sentence processing compared to the auditory/speech processes indexed by P100 and MMN. The failure to find a strong relationship between the T-complex measures and P100 or MMN suggests that these components are tapping into, at least, partially independent processes. The finding that T-complex was more often consonant with higher-level measures of linguistic processing support the suggestion that it is part of a system important to language. However, our findings do not provide information about the directionality of the relationship. It is entirely possible that adequate learning of language leads to changes in the neural substrate indexed by the T-complex. Furthermore, a few exceptions were also seen in the relationship between these higher-level measures and the T-complex, suggesting that there might be partial independence of these measures, although perhaps less so than for T-complex and MMN or P100. Each of these studies had fairly small samples, so it will be important to perform a

study using a larger sample to confidently determine the degree of relationship between the various measures.

The strongest statement we can make about these comparisons of different measures is that children with TLD rarely had more than two poor neurophysiological measures, with 15 of the 31 (48%) showing no poor measures, and 21 of 31 (68%) showing no more than one poor measure. In contrast, 14 of the 22 (64%) children with LI generally exhibited three or more poor neurophysiological measures. Of the seven children from the LI group who showed only one or two poor measures six participated in only one study. Thus, it is quite possible that these children would show additional poor neurophysiology, if they had participated in the other studies. It is important to point out that we had almost equal numbers of TLD and LI children who had participated in more than one study. For these children, the nine from the TLD group had a mean number of poor measures of 1.9 (range 0 to 4) and the ten from the LI group had a mean of 5.0 poor measures (range 2 to 7). (Poor T-complex amplitude or morphology was counted as poor only once, if poor across multiple studies). Only two of these ten LI children showed fewer than five poor measures. The implications of this finding will be addressed further below where we discuss the nature of SLI.

Relationship to T-complex in other studies

Relatively few studies have examined the T-complex components in children. Tonnquist-Uhlen and colleagues (2003) presented the most comprehensive developmental study to date. They found little change in the Ta and Tb latencies across the 7–10 year old age groups. Our latency measures for Na, Ta, and Tb are generally comparable to their study. Tonnquist-Uhlen et al. (2003) showed mean Ta latencies ranging from 92 to 137 ms (with SDs of 13 to 23 ms) for 7 to 10 year old children, with adults values falling between 91 and 112 ms for T7 and 81 and 99 ms for T8. Thus, their findings suggest that the function indexed by Ta is fairly mature in timing early in development. The Na component was found to significantly decrease in latency with age in the Tonnquist-Uhlen et al. study. In our data, there was no evidence of delayed Na peak latency for the children with SLI, and thus, no clear evidence of delayed maturation.

Our amplitude measures are not directly comparable to the Tonnquist-Uhlen study because we used a nose reference and they used an average reference. However, in re-referencing our data to an average of the 31 sites (excluding the eye channel) for the purpose of comparison (not shown), the Ta amplitudes become more negative by 1.5 to 2 μ V. This leads to amplitudes of around 0 μ V for the TLD groups (with a comparable shift for SLI children) measured from baseline, similar to those in the Tonnquist-Uhlen study.

Similar to Tonnquist-Uhlen et al., the participants in our study exhibited more well-defined peaks at the right compared to the left site. They also observed earlier latencies and greater RMS amplitudes over the right site; other studies also suggest a right bias, but in the Tonnquist-Uhlen study this pattern may be a contralateral bias, since they delivered the stimuli only to the left ear.

Other investigations examining the T-complex in children have shown presence of the Tb component at similar latencies to our study and that of Tonnquist-Uhlen et al. (Bruneau, Roux, Guerin, Barthelemy & Lelord, 1997; Ceponiene, Cheour & Näätänen, 1998). These studies did not specifically measure Na and Ta. Pang & Taylor (2000) also examined the maturation of Na (N1a) and Tb (N1c) and suggested earlier maturation of these components over the left compared to right site, and particularly to a speech sound for the Tb component. The latencies of these components are somewhat later, but the morphology looks similar to our study and the Tonnquist-Uhlen study. In particular, the Na and Tb components were

larger at right compared to left sites in younger groups, but at left compared to right for older groups (over age 13). Examination of the figures in Pang and Taylor, suggest that Ta shows a similar pattern of $R > L$ from 3 to at least 10 years of age.

The data from the Tonnquist-Uhlen study also support the claim that the T-complex components index different sources of neural generators than those indexed by the P1-N1b-P2 components. Several studies suggest that the major source of these components is best represented by radially-oriented dipoles in secondary auditory cortex (Naatanen & Picton, 1987; Scherg & Von Cramon, 1987; Ponton et al. 2002).

Tonnquist-Uhlen et al. (2003) argued that the robust presence of the Na, Ta and Tb components between 5 and 8 years of age indicate that the underlying neural generators mature earlier than for the N1b, which is measured at superior sites, and/or that they have a shorter response recovery time. In particular, N1b is completely masked by positivities (P1 and P2) at short ISIs (under 700 ms), but there is less effect of ISI on the T-complex (Ceponiene, Cheour & Naatanen, 1998). These findings suggest earlier maturation of the neural generators of the T-complex compared to N1b. It will be necessary to examine the maturation of the T-complex beginning with very young children (between 1 and 4 years of age) to determine whether the poor Ta amplitude and T-complex correlation measures found in our study reflect delayed maturation, since our children with TLD show no clear maturational changes between 6 and 11 years of age.

Evidence that deviant T-complex components index poor speech and language processing have been found in only a few studies, but considering that the T-complex generally has not been examined in ERP studies, these findings are notable. The earliest studies showed abnormalities to non-speech stimuli in children with severe language impairments (Mason and Mellor, 1984; Tonnquist-Uhlen, 1996). Bishop, Uwer and colleagues found poor correlation at the right temporal site between the mean waveform of typically-developing children and the individual waveforms of children with SLI to tone and speech stimuli (Bishop, Hardiman, Uwer, & von Suchodoletz, 2007). This finding may reflect the same poor waveform correlation we found, although the correlational measure in the Bishop study did not normalize the waveforms for amplitude and thus was sensitive to both amplitude and shape. Their data also used a mastoid reference, which makes it difficult to compare directly with our data, because the mastoid sites reflect the P1-N1-P2 complex. Several studies have shown delayed latencies of the Tb (or N1c) peak of the T-complex to tones or speech in children with autism (Bruneau, Roux, Adrien, Barthelemy, 1999; Dunn & Bates, 2005). Eight-year-old children with autism showed these delayed latencies, but in 11 year olds this delay was not found. In our experiments, we did not find delayed latencies of Tb in the children with SLI, but rather saw poor morphology correlation in the interval including Tb. This difference between studies may indicate that the source of speech and language disorders is somewhat different in children with SLI and those with autism. It would be important to know whether T-complex measures are predictive of language abilities in children with autism before deciding whether the delay in Tb latencies is related to speech and language, rather than to some more general developmental delay.

The functional significance of The T-complex

The timing and topography of the Ta component indicate that it indexes processing at the cortical level. Dipole source modeling of the T-complex components is consistent with sources on the lateral surface of secondary auditory cortex (Scherg & von Cramon, 1986; Ponton et al., 2002). Thus, Ta (and Na and Tb) appears to index neural processing in belt or parabelt areas of auditory cortex. Dipole source analyses and correlational comparisons of the P1-N1b-P2, measured at superior sites, and the T-complex, measured at T7 and T8, strongly indicate that these two series of peaks have different sources (Ponton, et al., 2002).

Furthermore, Tonnquist-Uhlen et al. (2003) argue that the Na, Ta and Tb components are, at least, partly independent from each other because they mature at different rates, and because the later components mature faster than the earlier ones (Tb earlier than Ta, Ta earlier than Na).

The Na, Ta and Tb components have been elicited to simple tone stimuli, as well as complex word forms, regardless of task. The relatively early time-frame, between 70 and 200 ms along with their task independence indicates that they can be considered obligatory in nature. However, this does not preclude their modulation by higher-level factors. The T-complex is claimed to be less sensitive to intensity manipulations and ISI than the P1-N1b (Carrillo-de la-Pena, 1999). However, Ceponiene et al. (1998) show changes in latency related to ISI of the N160 (Tb) that appear to be comparable to P1-N1b. It is possible that the “Tb” measured in their data is contaminated by the N1b, which inverts and can be clearly measured at T5 and T6 (Tonnquist-Uhlen, et al., 2003). The sensitivity to intensity and ISI along with a source in primary auditory cortex have led to the interpretation of N1b as a detection index of acoustic properties. The apparent lesser sensitivity of the T-complex components to physical properties leads to the inference that these components must index some other aspect of auditory processing. The latency and amplitudes of the T-complex components were quite similar across the different stimuli and experimental designs of our studies and the Tonnquist-Uhlen et al. study, also suggesting that registering the raw physical properties (such as duration, intensity, frequency, ISI) is not the sole functional focus of auditory processing in this cortical region. Systematic manipulation of what task and stimulus factors lead to modulation of the T-complex will be necessary to precisely identify the T-complex functions.

The early maturity of the subcomponents Ta and Tb suggests that the underlying neural generators may be in layer IV of secondary auditory cortex because earlier maturation of neurons are found in layer IV than in layers II and III. The thalamus projects parallel inputs to primary and secondary auditory cortex, and some or all of the T-complex components may serve as indices of this secondary cortex input, whereas the P1 has been shown to reflect input to the superior plane of primary auditory cortex (e.g., Ponton, et al., 2002). The N1b, in contrast, indexes neural activity in Layers II and III of superior temporal cortex and these layers generally mature later than Layer IV (Moore & Linthicum, 2007).

Given these considerations, it seems clear that P1, N1b and the T-complex components index different aspects of auditory processing. If some of the T-complex components are consistently shown to be reduced or deviant in children with disorders of speech and language, but not in children with non-language-related disorders then it will indicate that this pathway has particular importance for speech, as suggested by Tonnquist-Uhlen and colleagues (2003). Furthermore, our finding that the robustness of the T-complex measures matched better with higher-level language measures, such as the N400 to word discrimination and the temporal positivity (TP) asymmetry to sentence processing suggests that the T-complex components are part of a pathway important for language. An important avenue of research will be to define the pathways from the brainstem to secondary auditory cortex, and to higher-level speech perception and language areas to identify how these pathways, and the points in the pathway indexed by the T-complex components, contribute to speech perception and language processing. It will be of interest to see whether the delays and deviances found by Kraus and colleagues in brainstem responses in some children with learning problems (e.g., Wible, Nicol & Kraus, 2005) show stronger relationships with processing at the level indexed by the T-complex or with processing at levels indexed by P1 or N1b. Establishing these relationships could help define the functional pathways from periphery to central cortex.

It will also be important to examine the extent to which T-complex measures are modulated by higher-level linguistic factors. Our finding that the Ta amplitude was robust to real words for children with good language, whether or not they showed good amplitude for nonsense words merits further investigation.

The nature of SLI

We suggested in the introduction that it would be useful to look for factors that raise the risk of developing language impairment because there is considerable evidence that SLI has multiple factors. Poor auditory processing certainly appears to be one factor that contributes to language impairment, but the causal relationship between auditory processing and language impairment is still unknown. There are also questions about the best way to measure poor auditory processing and whether auditory processing, per se, is the problem or something else that leads to poor auditory processing, as well as language impairment. For example, more recently various general cognitive disorders have been suggested as underlying SLI, including poor working memory (Coady et al. 2005), poor cognitive control (e.g., Norbury, 2005; Im-Bolter et al, 2008; Marton, Kelmenson & Pinkhasova, 2008) or poor attention to speech (e.g., Shafer, et al., 2007) and these could bring about the appearance of poor auditory processing. It also appears that there is a genetic basis for some of these deficits, including deficits in phonological memory and in inflectional marking (Bishop, 2006). It would be of particular interest to see whether the Ta amplitude and T-complex morphology are related to either of these measures, and whether either measure can be linked to genetic rather than environmental factors.

Our study demonstrates that neurophysiological measures can give us insight on these questions. Our data suggest that between 70 and 200 ms signs of poor speech processing in auditory cortical regions are apparent in 75% of children with SLI whereas less than 15% of children with good language show such poor processing. These findings lend credence to the suggestion that poor processing in auditory cortex (although it may be specific to speech) is a significant contributing factor in SLI. The source of this poor processing, however, remains open for explanation. The T-complex peaks are obligatory components, but they could be influenced in a top-down fashion by other functions, such as language-specific speech sound representations, lexicality or attention. We found the Ta measures to be highly correlated across the passive and attend tasks in our experiments, suggesting some independence from attention, but we also found that the lexical status of a word appeared to affect Ta amplitude differently for the TLD and SLI children. Furthermore, it is possible that deficits in higher cognitive functions led to poor speech processing during development. Specifically, during development, infants become attuned to the relevant acoustic-phonetic information in their native language and develop automatic routines for selecting this information (see Strange & Shafer, 2008). Arguably, they need good attentional and memory skills to identify the relevant information and set-up these automatic routines. A number of developmental models have stressed the importance of attention in developing native-language phonology (e.g., Jusczyk, 1997; Werker & Curtin, 2005). It is also possible that the poor Ta-measures reflect a more general speech-processing deficit in the sense that these children lack the normal attraction to speech. In Shafer, et al. (2007) we found that the children with SLI had less evidence of attending to speech sounds in a passive task than children with TLD (specifically, less of a negative shift or Nd), which may reflect less attention to speech than for typically developing children.

Bishop and McArthur (2005) have also suggested that children with SLI show delayed maturation of auditory processing. They observed immature ERP morphology to auditory sounds in teenagers with SLI. In our data, there is no clear indication that the more negative Ta measures reflect immaturity. Indeed some of the youngest children with TLD (in the DET study) have large amplitude Ta measures. However, we used a fairly narrow age-range

(most of the children fell between 8 and 10 years of age); it will be necessary to examine even younger children to fairly evaluate this hypothesis. Furthermore, the immature ERP responses in the Bishop et al. study were found for obligatory potentials recorded at superior sites (P1-N1-P2), which have different sources and a different developmental timecourse than the T-complex, as discussed above. Dunn and Bates (2005) did see a delay in Tb latency for 8-year-old children with autism, but our data show no such delay of Tb latency in children with LI.

An important finding was that most of the children with LI showed multiple deviant brain measures and the majority of children with TLD showed no, or only one or two deviant brain measures. The different brain measures did not always show comparable performance, indicating that they were tapping into somewhat independent functions. This pattern of findings supports the claim that SLI (and LI) has multiple causes, but also goes further to suggest that any given child diagnosed as LI or SLI has more than one deficit leading to poor language. Our finding that 1/2 of the children with typical language showed deviant performance of one to three measures suggests that none of the processes indexed by these measures, alone, is essential for adequate language learning and processing.

In summary, our data support claims that many children with LI, and more narrowly, SLI have an auditory processing deficit, perhaps specific to speech or complex stimuli, but do not clarify the source of this deficit. It is possible that poor processing of these speech sounds reflects a deviant pattern of developing speech categories. Deficits in higher-level cognitive functions, such as attention and working memory, may have contributed to the poor speech processing found in these experiments, but studies of early development are necessary to test these hypotheses.

Conclusion

These experiments reveal that in our sample, 73% of the children with LI, but only 16% of the children with TLD have poor speech processing, as indexed by poor amplitude of the Ta component and poor T-complex waveform correlation. The timing of these components (between 50 and 200 ms), their lesser sensitivity to intensity and ISI, early developmental timecourse, source in secondary auditory cortex, and stronger relationship with higher-level language measures combine to suggest that the T-complex indexes higher order auditory processing than that indexed by P1-N1b, but also that it indexes input from the thalamus into deep layers. The finding that these T-complex measures are poor for such a large proportion of children with SLI, but good for most of those with TLD, suggests that this cortical region is highly important for speech processing underlying language development and processing. However, our data also suggest that deviant processing in this cortical region, by itself, does not underlie language impairment. The exact causal relationship between the poor processing indexed by these measures and language impairment remains unclear, but these results suggest that examining the development of the T-complex components in infants and children and its relationship to language acquisition and to other neurophysiological measures of language at these early ages will be important for addressing this question.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Left Temporal (T7) and right temporal (T8) Grand Mean ERPs to the function word “the” in the Determiner (DET) study for the TLD ($N = 12$) and SLI groups ($N = 8$). Na, Ta, and Tb peaks are labeled. The SLI Grand Mean does not include one LI participant who did not quite meet the SLI criteria.

Figure 2.

Left Temporal (T7) and right temporal (T8) Grand Mean ERPs to the vowel in the Passive (top) and Attend (bottom) conditions of the Short Vowel Study (SV) for the TLD ($N = 17$) and SLI groups ($N = 8$). Na, Ta, and Tb peaks are labeled. The SLI Grand Mean does not include three LI participants who did not quite meet the SLI criteria.

Figure 3. Left Temporal (T7) and right temporal (T8) Grand Mean ERPs to the vowel in the Passive (top) and Attend (bottom) conditions of the Long Vowel Study (LV) for the TLD (N = 11) and SLI groups (N = 9). Na, Ta, and Tb peaks are labeled.. The SLI Grand Mean does not include one LI participant who did not quite meet the SLI criteria.

Figure 4.

Left Temporal (T7) and right temporal (T8) Grand Mean ERPs to the Real word (top) and Non word (bottom) conditions of the Content Word Study (CW) for the TLD (N = 8) and SLI groups (N = 7). Na, Ta, and Tb peaks are labeled.

Figure 5.

Ta amplitude plotted against waveform correlation for each child at the left and right temporal sites. Red pluses are children with TLD, black circles, children with LI and black squares, children with additional clinical issues. The red triangles superimposed on other markers indicate low non-verbal IQ. The vertical and horizontal lines bifurcate the x and y axes at the median values.

Figure 6. Grand Mean ERPs at T8 to the Nonse and Real Words comparing both groups. The P380 is significantly more positive for the TLD than the LI group.

Table 1

Number (N), Sex, and Mean and SD (in parentheses) of test scores for all the children participating in the four experiments. The 14 SLI children and eight other children with LI, but also other issues are grouped together as LI.

Group	N	SEX	TONI	PPVT	REC	EXP
TLD	31	16F	104(18)	106(13)	111(11)	110(13)
LI	22	7F	92(10)	89(13)	89(14)	81(13)

Test of Non-verbal Intelligence (TONI); Peabody Picture Vocabulary Test (PPVT); Clinical Evaluation of English Language, Receptive (REC) and Expressive (EXP) scores.

Number (N), Sex, and Mean (SD in parentheses) of Age and test scores for the TLD and LI children (including SLI and LI) in the four experiments. Some children participated in more than one study.

Table 2

Study	N	SEX	AGE	TONI	PPVT	REC	EXP
DETTLD	12	6F	90 (15)	93(13)	101(14)	107(13)	104(10)
DETLI	9	1F	97 (13)	95(11)	95(16)	89(9)	86(12)
SVTLD	17	12F	109 (8)	110(18)	105 (11)	110(8.9)	111(11)
SVLI	11	3F	111(14)	91 (12)	88 (15)	85 (16)	83 (12)
LVTLD	10	6F	117(11)	102(14)	105(13)	110 (9)	104(10)
LVLI	10	3F	113(10)	91 (9)	91 (16)	91 (18)	82(15)
CWTLTD	8	3F	115(21)	102(12)	103(16)	110(17)	106(20)
CWLI	7	3F	114(17)	90(10)	80(12)	85(17)	79(14)

REC = CELF receptive, EXP = CELF expressive, and F = female, DET = Determiner, SV = Short Vowel, LV – Long Vowel, CW = Content Word.

Table 3

Design characteristics of the stimuli and tasks in the four studies.

Study	DET	SV	LV	CW
Stimuli	“the” repetition	standard /E/	standard /E/	first word in a pair of words
Examples	the-the-the-on a-the	E-E-E-E-E-E	E-E-E-E-E-E	bed, ged, cheeve, chief
Stimulus quality	natural-edited	synthetic	synthetic	natural-edited
Duration	75 ms	50 ms	250 ms	610 ms (SD = 115)
Segmental Properties	frication-schwa	F1= 650 Hz; F2 =1980 Hz;	F1= 650 Hz; F2 =1980 Hz	
Other		F3 =2174 Hz, F4 = 3175 Hz	F3 =2174 Hz, F4 = 3175 Hz	
F0	80 Hz	190 Hz	190 Hz	190–220 Hz range
Intensity	65 dB Spl	86.5 dB Spl	86.5 dB Spl	70 dB Spl
SOA	625 ms	600 ms	600 ms	M = 1390 ms
ISI	700 ms	550 ms	350 ms	2000 ms (Interpair)
Delivery	ear inserts	ear inserts	ear inserts	ear inserts
Stimulus N	100	1583	1583	128
Task(s)	Report sound heard	Passive - Video Attend-tone	Passive - Video Attend-tone	Same/different pair judgment
Other Stimuli	the in NONSENSE: The			
	bu ko gu-gu ki..	/I/	/I/	second word in pair
Other ISIs	“the in STORY: The curious little kitten...	54, 600-Hz tone	54, 600-Hz tones	e.g., “bed-ged”; “ged-ged”; “chief-chief”; 500 ms intra-pair interval
Other properties		/I/=F1=500 Hz, F2 =2160 Hz	/I/=F1=500 Hz, F2 =2160 Hz	
Other Tasks	STORY - picture-pointing probe	behavioral discrimination	behavioral discrimination	
	Count repeated syllables	Behavioral identification	Behavioral identification	

DET = Determiner, SV = Short Vowel, LV = Long Vowel, CW = Content Word.

Table 4

Na, Ta and Tb M (SD) latency and *p* for one-tailed t-tests.

Study Group	T8 Na	T8 Ta	T8 Tb	T7 Na	T7 Ta	T7 Tb
DET	<i>p</i> = .25	<i>p</i> = .48	<i>p</i> = .34	<i>p</i> = .34	<i>p</i> = .49	<i>p</i> = .19
TLD	77 (11)	114 (12)	149 (16)	83 (11)	124 (18)	153 (15)
SLI	74 (9)	114 (12)	145 (19)	86 (12)	124 (17)	146 (14)
SV Pass	<i>p</i> = .43	<i>p</i> = .12	<i>p</i> = .34	<i>p</i> = .24	<i>p</i> = .05	<i>p</i> = .04
TLD	80 (9)	121 (8)	163 (17)	91 (19)	127 (17)	181 (47)
SLI	80 (7)	116 (13)	160 (28)	86(10)	116 (12)	150 (28)
SV AT	<i>p</i> = .36	<i>p</i> = .29	<i>p</i> = .46	<i>p</i> = .36	<i>p</i> = .12	<i>p</i> = .02
TLD	80 (11)	118 (8)	163 (19)	91(22)	126 (16)	184 (43)
SLI	82 (7)	116 (11)	162 (24)	88 (11)	118 (17)	152 (24)
LV Pass	<i>p</i> = .16	<i>p</i> = .02	<i>p</i> = .16	<i>p</i> = .26	<i>p</i> = .45	<i>p</i> = .40
TLD	72 (19)	117 (11)	175 (10)	90 (10)	124 (16)	168 (12)
SLI	82(20)	135 (22)	180 (14)	85 (24)	125 (17)	166 (18)
LV AT	<i>p</i> = .17	<i>p</i> = .15	<i>p</i> = .13	<i>p</i> = .34	<i>p</i> = .10	<i>p</i> = .31
TLD	76 (16)	118 (12)	175 (20)	86(23)	124 (22)	166 (13)
SLI	83 (15)	126 (19)	166 (16)	83 (28)	111(18)	162 (22)
CW Non	<i>p</i> = .06	<i>p</i> = .05	<i>p</i> = .12	<i>p</i> = .16	<i>p</i> = .15	<i>p</i> = .33
TLD	81 (11)	109 (10)	147 (15)	86 (13)	111 (15)	151 (16)
SLI	92 (14)	118 (8)	160 (23)	94 (18))	.120 (15)	135 (25)
CW Real	<i>p</i> = .29	<i>p</i> = .36	<i>p</i> = .21	<i>p</i> = .48	<i>p</i> = .26	<i>p</i> = .37
TLD	86 (13)	115 (10)	154 (18)	86 (12)	111 (9)	149 (21)
SLI	90 (14)	118 (15)	161 (11)	86 (7)	107 (12)	145 (27)

p's < 0.1 are bolded. DET = Determiner, SV = Short Vowel, LV = Long Vowel, CW = Content Word.

Table 5

Mean, SD and p for comparisons of waveform correlations.

Group	DETT7	SVATT7	SVPT7	LVAT7	LVPT7	RWT7	NWT7
TLD mean (SD)	0.52 (0.40)	0.28 (0.55)	0.34 (0.50)	0.44 (0.32)	0.46 (0.31)	0.31 (0.42)	0.28 (0.52)
SLI mean (SD)	0.31 (0.56)	0.24 (0.65)	0.25 (0.59)	0.02 (0.38)	0.27 (0.35)	-0.03 (0.38)	0.04 (0.36)
two-tailed <i>p</i>	0.18	0.20	0.14	0.01	0.11	0.06	0.16
DETT8	SVATT8	SVPT8	LVAT8	LVPT8	RWT8	NWT8	
TLD mean (SD)	0.59 (0.36)	0.50 (0.36)	0.57 (0.34)	0.68 (0.31)	0.68 (0.32)	0.33 (0.37)	0.38 (0.28)
SLI mean (SD)	0.39 (0.32)	0.48 (0.28)	0.50 (0.32)	0.27 (0.63)	0.23 (0.62)	0.15 (0.45)	0.16 (0.29)
two-tailed <i>p</i>	0.11	0.26	0.18	0.04	0.03	0.20	0.08

p's < 0.1 are bolded and less than 0.05 are italicized. Studies: DET = Determiner, SV = Short Vowel, LV = Long Vowel, CW = Content Word.

Table 6

Ta, Na-Ta and Ta-Tb M (SD) amplitude and p for one-tailed t-tests.

Study	T8 Ta	T8 Ta-Na	T8 Ta-Tb	T7 Ta	T7 Ta-Na	T7 Ta-Tb
DET	p = .06	p = .07	p = .10	p = .07	p = .04	p = .42
TLD	5.64 (2.96)	7.45 (4.45)	3.94 (3.53)	3.02 (4.45)	5.08 (2.68)	2.33 (3.04)
SLI	3.25 (3.59)	4.51 (3.59)	1.99 (2.31)	0.63 (2.61)	3.06 (1.1)	2.05 (2.92)
SV Passive	p = .08	p = .05	p = .19	p = .02	p = .04	p = .04
TLD	3.58 (3.92)	4.73 (3.15)	3.66 (3.9)	2.37 (2.15)	2.32 (1.72)	3.73 (3.16)
SLI	1.57 (2.15)	2.94 (1.21)	2.44 (2.15)	.46 (2.03)	1.26 (.59)	1.54 (2.27)
SV Attend	p = .14	p = .12	p = .18	p = .02	p = .14	p = .03
TLD	2.54 (3.41)	3.84 (2.78)	3.68 (3.34)	1.99 (1.57)	1.98 (1.50)	3.28 (2.24)
SLI	1.18 (2.17)	2.65 (1.48)	2.57 (2.23)	.59 (1.52)	1.39 (1.0)	1.57 (2.16)
LV Passive	p = .02	p = .23	p = .03	p = .50	p = .19	p = .16
TLD	4.03 (2.49)	3.93 (2.46)	4.51 (3.11)	1.06 (1.69)	1.71 (1.75)	1.86 (1.50)
SLI	1.72 (1.63)	3.27 (2.15)	1.91 (2.06)	1.05 (1.15)	1.13 (.86)	1.24 (.98)
LV Attend	p = .06	p = .01	p = .04	p = .23	p = .01	p = .05
TLD	2.96 (2.19)	1.75 (1.31)	3.51 (3.2)	.76 (1.50)	1.76 (1.31)	1.78 (1.47)
SLI	1.44 (1.89)	0.58 (0.55)	1.42 (1.16)	1.22 (1.03)	.58 (.55)	.78 (.76)
CW Non	p = .04	p = .06	p = .18	p = .21	p = .16	p = .15
TLD	4.08 (2.73)	3.09 (2.78)	2.99 (1.59)	1.67 (2.78)	1.3 (1.18)	2.25 (1.12)
SLI	1.4 (2.5)	1.26 (.72)	2.08 (2.05)	.56 (2.38)	.80 (.48)	1.57 (1.30)
CW Real	p = .000	p = .10	p = .07	p = .06	p = 0.11	p = .45
TLD	3.76 (2.0)	2.99 (2.67)	2.84 (2.25)	1.92 (3.16)	2.62 (3.5)	2.02 (1.69)
SLI	-0.09 (.84)	1.51 (1.26)	1.37 (.88)	.44 (2.13)	0.88 (.68)	1.90 (1.45)

p's < 0.1 are bolded and less than 0.05 are italicized. DET = Determiner, SV = Short Vowel, LV = Long Vowel, CW = Content Word.

Table 7
Means SD and p-values for RMS comparisons and probability for one-tailed t-tests.

	DET7	SVAT7	SVPT7	LVAT7	LVPT7	RWT7	NWT7
TLD mean	2.15	1.23	1.22	0.85	0.82	1.63	1.27
SD	1.21	0.41	0.44	0.37	0.42	0.75	0.49
SLI mean	1.96	1.04	0.98	0.61	1.22	1.24	0.94
SD	0.88	0.63	0.58	0.23	0.79	0.74	0.43
p	0.35	0.18	0.13	0.06	0.10	0.17	0.10
	DET8	SVAT8	SVPT8	LVAT8	LVPT8	RWT8	NWT8
TLD mean	2.51	1.64	1.78	1.51	1.73	1.87	1.50
SD	1.25	0.78	0.97	0.86	0.94	0.75	0.67
SLI mean	1.99	1.32	1.42	1.12	1.33	0.88	1.04
SD	1.23	0.53	0.40	0.40	0.75	0.29	0.54
p	0.18	0.13	0.14	0.12	0.16	0.005	0.08

p's < 0.1 are bolded and less than 0.05 are italicized. DET = Determiner, SV = Short Vowel, LV = Long Vowel, CW = Content Word.

Table 8

Description of ERP measures for children who participated in multiple studies (DET = Determiner, SV = Short Vowel, LV = Long Vowel and CW = Content Word). Only poor measures are listed, and in the case that all measures were good, then the label "GOOD" fills the cell. Blank cells indicate that the child did not participate in that study.

ID	G	DET	SV	LV	CW
37	1	Poor T-complex amp & morph	GOOD	Poor T-complex morph	GOOD
40	1	Poor vertex pos, R>L TP	Poor T-complex amp		GOOD
46	1	GOOD	GOOD	Late Pass P100	
74	1		Poor T-complex morph, Poor MMN	Poor T-complex amp, late P100	
75	1	R>L TP	GOOD	GOOD	
80	1	GOOD	GOOD	GOOD	
97	1	Poor T-complex amp, R>L TP	GOOD		GOOD
102	1	Poor T-complex morph, Poor vertex pos	GOOD	GOOD	
115	1		Poor T-complex amp & morph	Poor T-complex amp & morph	Poor T-complex morph Poor Pz-pos (coda)
17	2	Poor T-complex amp & morph, poor vertex pos, R>L and poor L TP	Poor T-complex morph, poor MMN		
18	2	Poor T-complex amp & morph, poor vertex pos, R>L and poor L TP	Poor T-complex amp & morph, poor MMN		
22	2	Poor T-complex amp & morph, poor vertex pos, R>L and poor L TP		Poor T-complex amp & morph, late P100	
38	2	Poor T-complex amp & morph, R>L TP	Poor T-complex amp, poor MMN	Poor T-complex amp, late Pass P100	Poor T-complex amp & morph, late N400 coda, poor Pz-pos (onset & coda), poor (small pos) P380
47	2	GOOD	Poor MMN	Poor T-complex amp	
54	2			Poor T-complex morph, late P100	Poor T-complex amp & morph, late N400, poor Pz-pos (onset & coda), poor (neg) P380
59	2	Poor T-complex amp & morph, poor vertex pos, poor L TP amp	Poor T-complex amp & morph, Poor MMN		Poor T-complex amp & morph, no coda N400, poor (neg) P380
99	3			Poor T-complex amp & morph, late P100	Poor Ta amp, poor Pz-pos (onset & coda), poor (small pos for noise & neg for real) P380
111	2	Poor T-complex amp & morph, poor vertex pos, R>L TP	Poor MMN		
116	3	Poor T-complex amp	Poor T-complex amp & morph, poor MMN	Poor T-complex amp & morph	

Group (G): TLD = 1, SLI = 2 and LI = 3; ID = subject identification; amp = amplitude; morph = morphology; MMN = Mismatch Negativity; pos = positivity; neg = negative; R = right; L = Left; TP = temporal positivity; Pass = Passive; nonse = Nonsense words; real = Real words.

Table 9

Description of ERP measures for children who participated in only one study (DET = Determiner, SV = Short Vowel, LV = Long Vowel and CW = Content Word). Only poor measures are listed, and in the case that all measures were good, then the label “GOOD” is used. MMN was listed as poor, only if it were poor in both Attend and Passive conditions.

ID	Group	Study
9	1	DET-GOOD
56	1	DET-GOOD
55	1	DET-poor T-complex amp, R>L TP
110	1	DET-poor T-complex morph, poor L TP amp
xe	1	DET-GOOD
32	1	SV-GOOD
76	1	SV-poor T-complex morph
81	1	SV-GOOD
94	1	SV-GOOD
108	1	SV-GOOD
118	1	SV-poor T-complex amp & morph
125	1	SV-GOOD
xc	1	SV-GOOD
xd	1	SV-GOOD
31	1	LV-GOOD
41	1	LV-GOOD
98	1	LV-Late Attend P100
103	1	LV-poor T-complex morph
29	1	CW-poor T-complex amp & morph, late N400, poor Pz-pos (coda), poor (small pos) P380 amp
126	1	CW-poor PZ-pos (onset & coda)
xa	1	CW-GOOD
xb	1	CW-GOOD
65	3	DET-poor vertex pos, R>L TP
109	2	SV-poor T-complex amp & morph
19	3	SV-poor T-complex amp & morph
62	3	SV-poor T-complex amp
16	3	SV-poor T-complex amp & morph, poor MMN
24	2	LV-poor T-complex amp & morph
39	3	LV-poor T-complex amp & morph
70	2	LV-poor T-complex amp & morph, late P100
101	2	LV-GOOD (T-complex amp at the median)
14	3	CW-poor T-complex amp, late N400, poor Pz-pos (onset & coda), poor (neg) P380 amp
44	2	CW-poor T-complex amp & morph, late N400, poor Pz-pos (onset & coda)
88	2	CW-poor T-complex morph, no coda N400, poor Pz-pos (onset & coda)

TLD (Group = 1), SLI (Group = 2) and LI (Group = 3); ID = subject identification; amp = amplitude; morph = morphology; MMN = Mismatch Negativity; pos = positivity; neg = negative; R= right; L = Left; TP = temporal positivity.