Published in final edited form as:
Brain Res. 2011 May 10; 1389: 93–102. doi:10.1016/j.brainres.2011.02.010.

P300 as a measure of processing capacity in auditory and visual domains in Specific Language Impairment

Julia L. Evans, Ph. D. ccc.slp[1,*] and **Seth D. Pollak, Ph.D.**[2,3]
[1]School of Speech Language Hearing Sciences, San Diego State University
[2]Department of Psychology, University of Wisconsin-Madison
[3]Waisman Center for Human Development, University of Wisconsin-Madison

Abstract

This study examined the electrophysiological correlates of auditory and visual working memory in children with *Specific Language Impairments (SLI)*. Children with SLI and age-matched controls (11;9 – 14;10) completed visual and auditory working memory tasks while event-related potentials (ERPs) were recorded. In the auditory condition, children with SLI performed similarly to controls when the memory load was kept low (1-back memory load). As expected, when demands for auditory working memory were higher, children with SLI showed decreases in accuracy and attenuated P3b responses. However, children with SLI also evinced difficulties in the visual working memory tasks. In both the low (1-back) and high (2-back) memory load conditions, P3b amplitude was significantly lower for the SLI as compared to CA groups. These data suggest a domain-general working memory deficit in SLI that is manifested across auditory and visual modalities.

Keywords

SLI; working memory; n-back; ERP

1. Introduction

Stark and Tallal (1981) introduced the term Specific Language Impairment (*SLI)* to refer to a group of children who have difficulty acquiring and using language in the absence of any identifiable etiology.[1] These children display normal nonverbal intelligence, hearing, and socio-emotional abilities. Yet, a wide range of language difficulties are observed in these children including delayed onset and slower acquisition of lexical and grammatical forms, smaller vocabularies, and difficulty acquiring and using inflectional morphology and complex syntax (Leonard, 1998). Initially, these language impairments were believed to be specific to missing features of grammar in the linguistic system. But there is now

---

[*] **Address correspondence to:** School of Speech Language Hearing Sciences San Diego State University 5500 Campanile Drive San Diego, CA 92182 jevans@mail.sdsu.edu phone (619) 594-7907. .

[1] The terms language learning disabled and language impairment have been used in the literature to describe these children. However, although these children may also have concomitant difficulties in reading, SLI and dyslexia appear to be distinct, co-morbid disorders (See Catts et al., 2005; Snowling & Bishop, 2007).

considerable evidence that nonverbal cognitive mechanisms may underlie the language impairments seen in these children. Two cognitive mechanisms that have been examined extensively are the speed with which information can be manipulated and working memory capacity (D. V. M. Bishop, North, & Donlan, 1996; Ellis Weismer, Evans, & Hesketh, 1999; Gillam, Cowan, & Marler, 1998; Leonard, et al., 2007; Montgomery & Evans, 2009).

The slower speed of processing account holds that language impairments are secondary to an impaired global timing mechanism – the maximum rate at which a given cognitive operation can be executed (e.g., (Kail & Salthouse, 1994). On this view, children with SLI process each unit of information at a slower rate than typically developing peers (Kail & Salthouse, 1994). Consistent with this theory, children with SLI appear to process information 18% - 30% slower than normal language controls. Slower reaction times have been observed across verbal, nonverbal, motor, and visual modalities (Johnston, 1994; Kail & Salthouse, 1994; Miller, et al., 2006; Windsor & Hwang, 1999). Limited working memory capacity models suggest that children with SLI are able to simultaneously allocate their attentional resources to process and store verbal complex material. However, relative to their typical peers, they have limitations in cognitive capacity (Coady & Evans, 2008; Mainela-Arnold & Evans, 2005; Montgomery, 2002). Supporting this view, children with SLI show have reduced processing capacity for auditory as well as visual-spatial stimuli (Hoffman & Gillam, 2004; Johnston & Smith, 1989).

The speed at which one can process information and the amount of information one can retain at a given time are tightly integrated. For example, faster processing means faster rehearsal, which in turn can result in more information being successfully held in memory. However these two cognitive components also appear to be separable and independently contribute to the impairments in children with SLI (Leonard, et al., 2007).

Children’s manual motor and verbal response rates are typically used to measure processing speed in children with SLI. However, children with SLI have poor manual co-ordination (Habib, 2000), and are significantly slower, but no less accurate, than age-matched controls in the speed with which they can complete a range of different manual motor tasks (Hill, 2007). Therefore, we used a psychophysiological measure that is not dependent upon manual-motor processing to examine working memory in children with SLI. The P3b is a component of the event-related potential that is often studied with regard to information processing.

The modulation of the P3b amplitude appears to be related to context updating operations and subsequent memory storage (Polich, 2007). In individuals with neurological disorders, P3b amplitude is decreased in conjunction with increased latency of the P3b, and reflects a general slowing of cognitive processes secondary to neuro-degeneration (Polich, 2004). For cognitive tasks where individuals briefly experience a set of stimuli to memorize and then must determine if the probe stimuli is a part of the original stimuli set, P3b latencies increase (e.g. Sternberg, 1969). This increase in P3b latency with memory set size is believed to reflect the cognitive processes of memory search and category decision time (e g., Ford, Roth, Mohs, Hopkins, & Kopell, 1979, Strayer, Wickens, & Braune, 1987). However, for dual cognitive processing tasks that require the simultaneous updating, encoding, manipulating, and search components in working memory, Latency of the P3b is thought to reflect the time required to evaluate and classify stimuli and differentiates stimulus evaluation from response selection and execution (Fjell & Walhovd, 2001). P3b latency does not change as memory load is increased, but P3b amplitude decreases as memory load is increased. This differentiation in the modulation of P3b amplitude and latency is evident in *n*-back working memory tasks where individuals are presented with a series of stimuli and asked to determine whether a given stimulus item matches an item *n* items back in a sequence. As working memory load is increased by increasing *n* (e.g., 1-, 2-, 3-, etc), individuals are required to simultaneously store more items in memory while updating the contents of their working memory as each new item occurs in the series, and P3b peak amplitudes decreases (Watter, Geffen, & Geffen, 2001).

The poor motor skills in children with SLI undermines the validity of the slower speed of processing accounts of SLI and limits a direct test of speed of processing and limited processing capacity accounts of SLI. However, Watter et al. observed that behavioral accuracy decreased while reaction times increased as *n* increased (0-, 1-, 2-, and 3-back) during a visuospatial n-back task. P3b peak latency at electrode Pz did not differ significantly across the 1-, 2-, and 3-back conditions, although it ranged from 394ms-440ms within individual participants. P3b peak amplitude from midline electrodes was largest at parietal sites, decreasing through central and frontal electrode sites, however across load levels, P3b peak amplitude decreased progressively from 0-back to 3-back, with the magnitude of the *n*-back task-related amplitude effects being observed from parietal through frontal electrode sites. P3b peak amplitude was larger for match than nonmatch trials at Pz and Cz electrode sites, but no different at Fz. Thus, as memory load is increased across the 1-, 2-, and 3-back conditions, behavioral reaction times increases, P3b latency remains constant and P3b amplitude decreases, reflecting the increase in cognitive processing demands and the reallocation of attention and processing capacity away from the matching process to the working memory requirements of the task.

1.2 ERP studies in individuals with SLI

To date, the only P3b data in children who meet the exclusion criteria for SLI comes from oddball paradigms. In the auditory modality P3b, has been examined with pure tones or speech sounds (i.e., phonemes) and in the visual modality with stimuli such as geometric shapes (Jirsa & Clontz, 1990; Courchesne, Lincoln, Yeung-Courchesne, Elmasian, & Grillon, 1989; Lincoln, Courchesne, Harms, & Allen, 1993). Differences in P3b latency and amplitude between children with language impairments and normal language controls are mixed. For example, Courchesne, et al. (1989), compared the performance of children with autism to children with receptive language impairments (LI) and normal language controls. Although reaction times were slower for the LI as compared to the normal control group,

P3b latencies were no different for the LI or normal control groups in either the auditory or visual modalities. P3b amplitudes were significantly larger for the LI as compared to the normal controls in the auditory modalities, but not no different in the visual modality. Lincoln et al. (1993), in contrast, found no differences in P3b latency or amplitudes for children with language impairments and normal language controls during passive or active auditory detection tasks. In both groups, P3b amplitude decreased with increased stimulus probability (cf. Hillyard & Picton, 1987; Johnson, 1988), and increased under conditions requiring an active as compared to passive responses – consistent with the view that P3b amplitude is modulated by active attention as well working memory demands. The poor motor skills in children with SLI undermines the validity of the slower speed of processing accounts of SLI and limits a direct test of speed of processing and limited processing capacity accounts of SLI.

The current study was designed to test processing speed and working memory in children with SLI. If SLI is primarily a speed of processing deficit, we should see slower behavioral reaction times and P3b latencies for children with SLI regardless of processing load. If SLI reflects limited processing capacity, we should see differences in behavioral accuracy and P3b amplitude for SLI and controls, but no difference in P3b latencies. We also sought to determine whether the cognitive processing deficits in SLI are specific to the linguistic domain by contrasting children's performance in auditory and visual modalities.

2. Results

All behavioral and psychophysiological analyses were corrected using the Greenhouse-Geisser correction applied to probability values to adjustment for repeated measures. A repeated measures analysis of covariance (ANCOVA) was used for all analyses, with group (SLI, CA) as between-subjects factor, modality (visual, auditory) and load (1-back, 2-back) as within-subjects factors, and nonverbal IQ as a covariate. For ERP analyses, target (match, non-match) was included as an additional within-subject variable.

To address a potential problem of general measures of accuracy where children's sensitivity to correct responses is confounded with biases to select (or avoid) particular stimuli, two signal detection statistics were calculated: Pr, a discrimination index representing the probability that an item will cross a recognition threshold, and Br, a bias index that reflects how much certainty the child requires to select a particular match. Children's patterns of hit rates and false alarms were combined into two statistics that describe children's (a) sensitivity to differences between emotion expressions and (b) response biases or willingness to define an ambiguous stimulus as a target. Typically, signal detection measures such as *d'* and B' (or the nonparametric approximations, A' and B") are used to measure sensitivity and bias, respectively. However, when subjects' recognition accuracy is low, these statistics have been shown to lack independence, and threshold models have been suggested as more appropriate measures (see Pollak et al., 2000). In contrast to high-threshold models, both the standard signal detection and nonparametric functions asymptotically reach the hit and false alarm axes quickly. Thus, Pr (the discrimination index) and B r (the bias index) allow observation of bias differences among participants even when performance is poor, whereas other measures are less effective as overall accuracy decreases. Formulae used to calculate these measures were taken from Pollak and colleagues (Pollak, Cicchetti, Hornung, & Reed, 2000).

Behavioral Analyses

Accuracy—Performance was significantly better for both groups in the auditory (Pr = .87) as compared to the visual (Pr = .71) modalities, F (1, 17) = 18.41, p < .001 (Figure 1). Group by load F (1, 17) = 7.33, p < .01 and group by modality F (1,17) = 4.358, p = .05 were also observed. Analysis of simple effects for modality (visual and auditory) for Pr collapsing across load revealed a significant modality by group effect for the auditory condition, F (1,17) = 9.527, p = .007 where children with SLI had significantly lower Pr values for the auditory modality compared to controls (SLI = .792; Control = .946). Analysis of simple effects for load collapsing across modality revealed a significant group effect for the 2-back F (1,17) = 5.418, p =.033, where the children with SLI had significantly lower Pr scores than the controls for the high load (2-back) condition (SLI = .550; Controls = .762).

Analysis of Br (response bias) values revealed no significant groups differences F (1,17) = .689, p <. 05, nor any significant group interactions, indicating no significant bias response between the groups for any condition. A significance main effect was found for modality F (1,17) = 4.583, p < .05, indicating that all children responded more conservatively for the visual modality. A load by modality interaction also was observed F (1,17) = 4.874, p <05. Post hoc analysis revealed that the children were responding more conservatively for 2-back as compared to 1-back conditions F (1,17) = 5.093, p <. 05.

Response time—Reaction Times (RT) for the SLI group were no slower than the CA group F (1, 17) = .383, *ns*, with both groups responding more quickly in the visual as compared to the auditory modality, F (1, 17) = 9.028, $p < .01$, (Figure 2). In the auditory modality, a group by load interaction was observed. The SLI group was *faster* than the CA group in the low load (1-back) condition and *slower* than the CA group in the high load condition, *F* (1, 17) = 4.120, p < .05.

Electrophysiological analyses

Auditory ERPs—P3b emerged at approximately 340 ms post stimulus that was maximal over the parietal region. A main effect was observed for target, *F* (1,18) = 336.57, *p* < .001, with higher voltages to matches versus non-matches. A site by target interaction was also significant, *F* (2,18) = 19.42, *p* < 001 with responses being greatest to matches, *F* (2,18) = 39.62, *p* < .01, as shown in Table 2.

Using P3b amplitudes at Pz for matches as the dependant variable, a repeated measures ANOVA revealed a main effect for group, indicating that P3b amplitudes were lower for the SLI group as compared to the CA group, *F* (1, 18) = 11.24, *p* < .01. However, this effect was qualified by a group by load interaction, *F* (1, 18) = 10.10, *p* < .01. This interaction reflects that P3b amplitudes for the SLI group were lower in the high memory load condition as compared to the CA group, *F* (1, 18) = 16.62 *p* < .001. P3b latencies did not differ between groups or across conditions, suggesting that neither group status nor condition effected processing speed, *F* (1, 18) = 1.31, *n.s.* (Table 3, Figure 3).

Visual ERPs—P3b emerged at approximately 440 ms post stimulus and was maximal over the parietal region. Matches had higher voltages than non-matches, *F* (1,18) = 20.90, *p* < .001. A site by target interaction was also significant, *F* (2,18) = 8.057, p = .002 (Table 4). Using P3b amplitude at Pz as the dependent variable, a repeated measures ANOVA revealed a main effect for group, where P3b amplitudes were significantly smaller for the SLI group as compared to the CA group, *F* (1,18) = 4.82, p < .05. A main effect for load was also observed, *F* (1,18) = 14.29, *p* < .001, where P3b amplitude was significantly lower in the high (2-back) memory load as compared to low load (1-back) conditions (Table 5). P3b latencies did not differ between groups or across the low and high load conditions, indicating that, as for the auditory modality, neither group status nor condition effected P3b latencies in the visual modality, *F* (1, 18) = 2.25, *n.s*. Grand averages are shown in Figure 4.

3. Discussion

The results of this experiment suggest that both processing speed and working memory are co-morbid deficits in children, and that these processing deficits may operate slightly differently in the auditory and visual modalities. The typically developing children in our control group showed patterns of results that follow the predictions based on the extant literature: their P3b amplitudes decreased with increased demands on working memory, regardless of modality. These changes in amplitude are believed to reflect the neural generators underlying working memory (Kok, 2001). In contrast, the children with SLI had greater difficulty as memory demands increased. While the children with SLI maintained adequate behavioral performance on the visual working memory tasks, their P3b responses were attenuated. This suggests that their behavioral accuracy comes at a higher processing “cost” not observable from overt behavior alone. When presented with auditory information, children with SLI performed similarly to those children in the control group only when memory demands were low. When demands on working memory increased, the children in the SLI group evinced decreased accuracy and P3b amplitudes compared to controls.

It is noteworthy that when working memory demands increased, children with SLI had slower reaction times. Yet, there were no differences in these children’s ERP latencies. This pattern of data raises the possibility that behavioral methods may confound slow manual motor responses with slowed cognitive processing among children with SLI. Future research should continue to explore this possibility.

Although SLI is thought to be a disorder primarily of language processing, the present data suggest deficits in auditory as well as visual domains. In the auditory modality, increased working memory affected behavioral accuracy, response time, and P3b amplitudes for children with SLI. But when these children processed visual information, we also observed low P3b amplitudes, suggesting more effortful processing of the stimuli for children with SLI. In the auditory modality, P3b peak latencies were no different for the SLI and CA groups in any condition, and only in the auditory high memory load condition did we observe the “classic” slower reaction times characteristic of slower speed of processing in SLI. If one were to examine the behavioral and EEG data in the auditory 2-back condition only for the SLI and CA groups, one might infer that slower speed of processing in children with SLI is the result of slower manual motor skills and not slower higher-level cognitive processing speed. However, the data from the 1-back and 2-back conditions together suggest that, in the auditory modality, there are trades-offs between processing demands and manual reaction time speed in children with SLI. Specifically, as processing demands increased (e.g., 1- to 2-back), reaction time and behavioral accuracy decreased for the SLI group as compared to the CA group as the children with SLI begin to experience difficulty allocating their cognitive resources between the storage and matching aspects of the task. The P3b latencies did not differ across the 1- and 2-back conditions, nor did they differ for the SLI and CA groups. This suggests that, although increased processing demands did not affect speed of cognitive processing (e.g., P3b latencies) in the children with SLI, it disrupted manual motor coordination and/or manual “decision” speed to a greater degree for SLI as compared to the CA group.

It is possible that reduced P3b amplitudes in the auditory and visual modalities in the SLI group reflect different underlying impairments. In the auditory condition, reduced P3b amplitudes might be reflecting an immature auditory system. Bishop and colleagues have suggested that the rate of development of the auditory system in children with SLI lags behind that of typically developing children (D. V. Bishop & McArthur, 2004, 2005). Developmental changes in P3b waveforms in typically developing children occur between the ages of 5;0 and 9;0, and are characterized by decreased amplitude and increased latency (see Bahramali et al., 1999).

Although there are no developmental data for the P3b in *n*-back tasks, data suggests that although children ages 7-12 evidence a similar hemisphere asymmetry in brain activation as adults ages 20-29, the increase in activation with increases in working memory load seen in adults in frontal and parietal cortical regions is absent in children (Thomason, et al., 2009). It is possible that P3b amplitudes also change developmentally with age in typically developing children, reflecting an increased ability to allocate resources between the attention and working memory aspects of n-back tasks. Thus it might be that developmental changes in P3b amplitude will prove to be similar to the developmental changes seen in the N400 that also reflect changes in working memory resources in children (Holcomb, Coffey, & Neville, 1992).

It is possible that reduced P3b amplitudes for the SLI group were due to lexical encoding deficits instead of deficits in the ability to maintain the target in memory. Although much of the research has focused on the morpho-syntactic deficits in SLI (cf. Leonard, 1998), children with SLI have significant deficits in phonological working memory (Coady & Evans, 2005), are consistently slower than peers in lexical retrieval tasks and require more of the acoustic signal to recognize spoken words (Lahey & Edwards, 1996; Mainela-Arnold, Evans, & Coady, 2008). Although the children with SLI in this study had significant deficits on the Nonword Repetition task – a measure of phonological encoding, the design of this study does not allow us to disentangle the extent to which deficits in auditory working memory are due to difficulty at the level of encoding or maintaining the lexical items in memory. However, a small but growing body of work suggests that lexical and syntactic representations in children with SLI may be degraded and/or poorly specified and require greater attentional resources to inhibit linguistic competitors during lexical processing (Bishop, 2000; Coady & Evans, 2008; Evans, 2001; Joanisse & Seidenberg, 2003; Mainela-Arnold, et al., 2008). Thus, the reduced P3b amplitudes observed for the children with SLI in this study may not reflect reduced working memory capacity but instead the demand for greater cognitive resources to maintain degraded representations in memory while inhibiting extraneous information. Research designs that modulate both the P3b and N400 could prove extremely valuable in characterizing the unique contributions of lexical encoding, maintenance, and retrieval in verbal working memory.

In the visual modality, the children may have been using a verbal rehearsal strategy and the reduced P3b amplitudes are not been a reflection of deficits in visual working memory, but are also due to lexical encoding and retrieval deficits. However, given that RTs were the same for the SLI and CA groups in both of the visual condition, this that lexical encoding deficits may not have been the primary factor. In particular, if the children were using a verbal rehearsal strategy the faces would presumably require “labels” that are several words long (i.e., *older man with white hair)*. The SLI groups’ poor phonological working would significantly interfere with their ability to encoding and maintaining these verbal descriptions in memory, resulting in significantly slower RTs for the SLI group on both the low and high memory load conditions as compared to the CA group. There is a growing body of work showing visual working memory and visual processing deficits in SLI (Archibald & Gathercol, 2007; Gillam, Cowan & Marler, 1998; Johnson & Ellis Weismer, 1983) that suggests that working memory deficits are not confined to the auditory modality and argues for direct investigation of the nature of visual processing deficits in SLI children.

Taken together, the RT and P3b latencies data are consistent with Windsor and Hwang’s (1999) argument that RT data alone can not differentiate between an impairment where cognitive processes are slowed but speed of sensory-motor processing is not and one where cognitive processes are not slowed and sensory-motor processes is. The present study employed only one type of working memory task. Additional research is necessary to determine whether the “slower speed of processing” seen in children SLI is a manifestation of motor control/co-ordination difficulties or higher-level cognitive representations and processing.

An important outcome of this study is the pattern modulation of the P3b waveform in *n*-back task as compared to oddball paradigms. These data show that differences in P3b amplitude are reflective of different aspects of processing loads depending upon the experimental paradigm employed. Specifically, in traditional oddball paradigms, P3b amplitude increases when stimulus probability is decreased, or under conditions requiring active attention and response demands on the part of the subject. However, in the *n*-back task, the dual processing requirements of the task, as *n* increases, manifests as *reduced* P3b amplitude, reflecting the allocation of attention and processing capacity away from the matching aspect of the task, to the working memory requirements.

Methodologically, the inclusion of the ERP data in this study provided valuable information not available from the reaction time data alone. Specifically, these data indicate that speed of processing in SLI needs to be examined within a framework that allows for speed of mental manipulation as well as manual response before a general speed of processing account can be put forth as an account of the language impairments in these children. A novel finding from this study is that the combined behavioral and ERP data revealed that children with SLI may be behaviorally as accurate as their peers (visual working memory), however this accuracy comes at higher processing costs as compared to typical children. Importantly, the results from this study show that behavioral performance for children with SLI may be similar to that of their peers, but without independent physiological measures of “effort” researchers will not know if children with SLI and their peers similarly near the limits of their processing capacity. If, for many cognitive and linguistic processing tasks, children with SLI are able to achieve behavioral performance that is similar to their peers, but it comes at higher processing costs, this clinical population will exhibit greater variability and heterogeneity as compared to normal language control groups, and pattern that theoretical accounts of SLI currently do not address.

4. Method

Participants

A total of 20 adolescents (ages 11;9-14;10), ten with Specific Language Impairment and ten chronologically age-matched (CA) controls, participated in the study. They were part of a large group of participants in an on-going National Institutes of Health (NIH) funded project being conducted by the first author investigating cognitive processing in SLI. Gender composition was the same for both groups (4 females, 6 males per group) and included 15 Caucasians, 4 African Americans, and 1 Hispanic adolescent. All participants met the following inclusion criteria: (a) nonverbal intelligence at or above 85 as measured by either the Leiter International Performance Scale (Roid & Miller, 1997) or the Columbia Mental Maturity Scale (Burgemeister, Blum, & Lorge, 1972), (b) passing a pure-tone audiometric screening at 20 dB HL at 500, 1000, 2000, and 4000 Hz at time of testing, (c) absence of oral and speech motor disabilities, (d) vision and physical/motor skills within normal limits, (e) right handed preference, and (f) from monolingual, English-speaking homes, (h) no history of cognitive delay, emotional or behavioral disturbances, motor deficits, significant birth history, or frank neurological signs including seizure disorders or use of medication to control seizures base on parent report.

Table 1 shows the standardized assessment measures for the two groups. Nonverbal I.Q. was greater than 85 for all children. Standard scores on the Clinical Evaluation of Language Fundamentals – Revised (Semel, Wiig, & Secord, 1987) for the SLI group were one SD or more below the mean on *both* Expressive and Receptive Composite Language Scores of the CELF-R. Verbal working memory was assessed by the NonWordRepetion Task (Dollaghan & Campbell, 1998). All children with SLI had a classification of Language Impairment in the their school, had received speech and language services throughout their school years, and were receiving language therapy from Speech Language Pathologists at the time of the study. The participants in the CA group were administered the three expressive subtests and one receptive subtest, Oral Directions, to confirm normal language status. The CA group had composite Expressive Language Scores of 85 or greater and Oral Directions subtest scores of 8 or greater. Following their participation in the larger on-going project, the children returned to the lab for two visits to complete the ERP study.

Procedure

Children participated in a 2 × 2, modality (auditory, visual) by memory load (low, high) *n*-back working memory task. The two memory loads were 1-back and 2-back. In the auditory condition, children heard a series of words. In the visual condition they saw a series of human faces with neutral affect. The stimuli duration, inter-stimulus interval, and hit rate in the auditory and visual modalities were the same. All stimuli were 800 ms in duration with an inter-stimulus interval of 1.6 seconds. The 1-back condition consisted of 160 trials with

48 matches (30% hit rate) and never contained more than one consecutive hit in a row. The 2-back condition consisted of 250 trials with 60 matches (24% hit rate) and never contained more than two consecutive hits in a row.

Subjects sat approximately 80 cm from a 20 cm computer screen in an electrically shielded, sound attenuated room. For the auditory condition, linked ear clips connected to insert earphones were placed in the subject's ears and stimuli were presented binaurally. Children were asked to press a button on a button-box as soon as they heard/saw a target word/face that matched a word/face they had heard/seen 1- or 2- items back in the sequence. To ensure that the children understood the task, at the onset of the experiment, prior to each trial block, children completed 10 practice trials. Children were required to complete all 10 training trials correctly before continuing to the experimental task. All 20 subjects successfully completed the practice trails. Children made two visits to the laboratory. During the two visits, children completed either the visual or the auditory condition of the ERP paradigm, with order being counterbalanced across the groups. During each visit, children completed the 1-back condition followed by the 2-back condition.

Electroencephalography (EEG) was recorded from Ag-AgCl electrodes attached to the scalp with a Lycra Electro-Cap, using Fp1, Fp2, F3, F4, F7, F8, C3, C4, P3, P4, T3, T4, T5, T6, O1, O2, Fz, Cz, Pz, Oz, electrode sites of the International 10-20 System and referenced to linked earlobes. A mid-forehead electrode served as ground. NeuroScan amplifiers (with 16-bit A-D conversion) were set for half-amplitude band pass at .01 to 100 Hz and EEG was sampled at 1000 Hz. Skin impedances at all electrode sites were maintained below 5 Kohms. Four EOG channels were placed horizontally and vertically from facial electrodes lateral to the left and right outer canthi and supra- and infra-orbital ridges, respectively, for eye-movement detection. EEG and EOG were averaged off-line for epochs of 2000 ms, starting with −200 ms before onset of stimuli and ending 1799ms before onset of the next subsequent stimuli. All trials with overt response errors or amplifier blocking were excluded from the ERP analysis. EEG was digitally filtered with a band pass filter of .1 to 30 Hz and then baseline corrected. Any epochs having a voltage in any of the channels exceeding 250 μV were automatically excluded. To eliminate ocular artifact on EEG, EEG data were adjusted for their regression on EOG, separately for blinks and other eye movements (Gratton, Coles, & Donchin, 1983). As a result, the adjusted EEG data had no correlation with the corresponding EOG data. ERPs were derived for match- and non-match trials by averaging the EEG data separately. A computer algorithm identified the largest positive/negative value of the subject's grand average at the electrode sites at which the component was maximal within a time window based upon the entire sample's average.

Stimuli

Auditory stimuli consisted of 24 words (12 monosyllabic common nouns and verbs). Each word was spoken twice, once by a male and once by a female speaker. Stimuli were recorded in a sound attenuated room using an Audio-Technica lapel lavaliere microphone ATR35s, recorded in stereo by a Sony minidisc player model MZ-R37. Using Sound Edit 16, white noise was added to the end of each word so that the duration of each auditory stimulus equaled 800 milliseconds (ms). All words also were matched for intensity (dB) with no greater that +/_ 4.5 dB difference based upon the intensity (volts) of the first vowel of each word. Stimuli were presented at 95 dB SPL.

Visual stimuli consisted of twenty-four faces (12 males, 12 females, 16 Caucasians, 8 Asians) that were slide-scanned from a validated set of pictures having neutral facial affect (Ekman & Friesen, 1976). Adobe Photoshop 6.0 was used to recreate the faces in gray scale and remove features surrounding the face (e.g. shoulders, hair, etc.) using black filler. Faces were centered on the screen and adjusted for image size (width = 300, height = 405 pixels).

Acknowledgments

These experiments would not be possible without the participation of many children and their families, for whose collaboration we are extremely appreciative. This research was supported by grants from the NIH- National Institute of Deafness and Other Communicative Disorders to Julia L Evans, (R01DC005650) and the National Institute of Mental Health to Seth Pollak (R01MH61285, R01MH68858). Infrastructure support was provided by the Waisman Center's P30-HD03352 (M. Seltzer, Center Director).

References

Bishop DVM, McArthur GM. Immature cortical responses to auditory stimuli in specific language impairment: evidence from ERPs to rapid tone sequences. Dev Sci. 2004; 7(4):F11–18. doi: 10.1111/j.1467-7687.2004.00356.x. [PubMed: 15484585]

Bishop DVM, McArthur GM. Individual differences in auditory processing in specific language impairment: a follow-up study using event-related potentials and behavioural thresholds. Cortex. 2005; 41(3):327–341. doi:10.1016/S0010-9452(08)70270-3. [PubMed: 15871598]

Bishop DVM. How does the brain learn language? Insights from the study of children with and without language impairment. Dev Med Child Neurol. 2000; 42(2):133–142. doi:10.1017/S0012162200000244. [PubMed: 10698331]

Bishop DVM, North T, Donlan C. Nonword repetition as a behavioural marker for inherited language impairment: evidence from a twin study. J Child Psychol Psychiatry. 1996; 37(4):391–403. doi: 10.1111/j.1469-7610.1996.tb01420.x. [PubMed: 8735439]

Burgemeister, B.; Blum, HL.; Lorge, I. Columbia Mental Maturity Scale. Version 3rd ed. Psychological Corporation; San Antonio, TX: 1972.

Coady JA, Evans JL. Uses and interpretations of non-word repetition tasks in children with and without specific language impairments (SLI). International Journal of Language & Communication Disorders. 2008; 43(1):1–40. doi:10.1080/13682820601116485. [PubMed: 18176883]

Dollaghan CA, Campbell TF. Nonword repetition and child language impairment. Journal of Speech, Language, and Hearing Research. 1998; 41:1136–1146.

Ekman, P.; Friesen, W. Pictures of Facial Affect. Consulting Psychologists Press; Palo Alto, CA: 1976.

Ellis Weismer S, Evans JL, Hesketh LJ. An examination of verbal working memory capacity in children with specific language impairment. Journal of Speech, Language, and Hearing Research. 1999; 42:1249–1260.

Evans JL. An emergent account of language impairments in children with SLI: Implications for assessment and intervention. Journal of Communication Disorders. 2001; 34:39–54. doi:10.1016/S0021-9924(00)00040-X. [PubMed: 11322569]

Fjell AM, Walhovd KB. P300 and neuropsychological tests as measures of aging: scalp topography and cognitive changes. Brain Topogr. 2001; 14(1):25–40. doi:10.1023/A:1012563605837. [PubMed: 11599530]

Gillam RB, Cowan N, Marler JA. Information processing by school-age children with specific language impariment: Evidence from a modality effect paradigm. Journal of Speech, Language, and Hearing Research. 1998; 41:913–926.

Gratton G, Coles MG, Donchin E. A new method for off-line removal of ocular artifact. Electroencephalogr Clin Neurophysiol. 1983; 55(4):468–484. doi:10.1016/0013-4694(83)90135-9. [PubMed: 6187540]

Habib M. The neurological basis of developmental dyslexia: an overview and working hypothesis. Brain. 2000; 123(Pt 12):2373–2399. doi:10.1093/brain/123.12.2373. [PubMed: 11099442]

Hill EL. The nonspecific nature of specific language impairment: a review of the literature with regard to motor impairments. International Journal of Language & Communication Disorders. 2007; 36:149–171. doi:10.1080/13682820010019874. [PubMed: 11344592]

Hoffman LM, Gillam RB. Verbal and spatial information processing constraints in children with specific language impairment. J Speech Lang Hear Res. 2004; 47(1):114–125. doi: 10.1044/1092-4388(2004/011). [PubMed: 15072533]

Holcomb PJ, Coffey SA, Neville HJ. Visual and auditory sentence processing: A developmental analysis using event-related brain potentials. Developmental Neuropsychology. 1992; 8(2-3):203–241. doi:10.1080/87565649209540525.

Joanisse MF, Seidenberg MS. Phonology and syntax in specific language impairment: evidence from a connectionist model. Brain Lang. 2003; 86(1):40–56. doi:10.1016/S0093-934X(02)00533-3. [PubMed: 12821414]

Johnston, JR. Cognitive abilities of children with language impairment. In: Watkins, R.; Rice, M., editors. Specific language impairment in children. Brookes Publishing Company; Baltimore, MD: 1994. p. 107-121.

Johnston JR, Smith LB. Dimensional thinking in language impaired children. J Speech Hear Res. 1989; 32(1):33–38. [PubMed: 2704199]

Kail R, Salthouse TA. Processing speed as a mental capacity. Acta Psychol (Amst). 1994; 86(2-3): 199–225. doi:10.1016/0001-6918(94)90003-5. [PubMed: 7976467]

Kok A. On the utility of P3 amplitude as a measure of processing capacity. Psychophysiology. 2001; 38(3):557–577. doi:10.1017/S0048577201990559. [PubMed: 11352145]

Leonard, LB. Children with specific language impairment. MIT Press; Cambridge, MA: 1998.

Leonard LB, Ellis Weismer S, Miller CA, Francis DJ, Tomblin JB, Kail RV. Speed of processing, working memory, and language impairment in children. J Speech Lang Hear Res. 2007; 50(2): 408–428. doi:10.1044/1092-4388(2007/029). [PubMed: 17463238]

Mainela-Arnold E, Evans JL. Beyond capacity limitations: determinants of word recall performance on verbal working memory span tasks in children with SLI. J Speech Lang Hear Res. 2005; 48(4): 897–909. doi:10.1044/1092-4388(2005/062). [PubMed: 16378481]

Mainela-Arnold E, Evans JL, Coady JA. Lexical representations in children with SLI: Evidence from a frequency-manipulated gating task. Journal of Speech, Language, and Hearing Research. 2008; 51(2):381–393. doi:10.1044/1092-4388(2008/028).

Miller CA, Leonard LB, Kail R, Zhang X, Tomblin JB, Francis DJ. Response time in 14-year-olds with language impairment. Journal of Speech, Language, and Hearing Research. 2006; 49(4):712–728. doi: 10.1044/1092-4388(2006/052).

Montgomery JW. Understanding the language difficulties of children with specific language impairments: Does verbal working memory matter? American Journal of Speech-Language Pathology. 2002; 11(1):77–91. doi:10.1044/1058-0360(2002/009).

Montgomery JW, Evans JL. Complex sentence comprehension and working memory in children with specific language impairment. J Speech Lang Hear Res. 2009; 52(2):269–288. doi: 10.1044/1092-4388(2008/07-0116). [PubMed: 18723601]

Polich J. Updating P300: an integrative theory of P3a and P3b. Clin Neurophysiol. 2007; 118(10): 2128–2148. doi:10.1016/j.clinph.2007.04.019. [PubMed: 17573239]

Pollak SD, Cicchetti D, Hornung K, Reed A. Recognizing emotion in faces: developmental effects of child abuse and neglect. Dev Psychol. 2000; 36(5):679–688. doi:10.1037/0012-1649.36.5.679. [PubMed: 10976606]

Roid, M.; Miller, L. Leiter International Performance Scale. Stoelting; Wood Dale, IL: 1997.

Semel, E.; Wiig, E.; Secord, W. Clinical Evaluation of Language Fundamentals - Revised. Psychological Corporation; San Antonio, TX: 1987.

Stark RE, Tallal P. Selection of children with specific language deficits. Journal of Speech and Hearing Disorders. 1981; 46(2):114–122. [PubMed: 7253588]

Thomason ME, Race E, Burrows B, Whitfield-Gabrieli S, Glover GH, Gabrieli JDE. Development of spatial and verbal working memory capacity in the human brain. Journal of Cognitive Neuroscience. 2009; 21(2):316–332. doi:10.1162/jocn.2008.21028. [PubMed: 18510448]

Watter S, Geffen GM, Geffen LB. The n-back as a dual-task: P300 morphology under divided attention. Psychophysiology. 2001; 38(6):998–1003. doi:10.1111/1469-8986.3860998. [PubMed: 12240676]

Windsor J, Hwang M. Testing the generalized slowing hypothesis in specific language impairment. J Speech Lang Hear Res. 1999; 42(5):1205–1218. [PubMed: 10515516]

Research Highlights

- Children with Specific Language Impairment show auditory memory deficits when memory demands are high
- These children also showed difficulties in the visual working memory tasks.
- These data suggest a domain-general working memory deficit in SLI that is manifested across auditory and visual modalities.

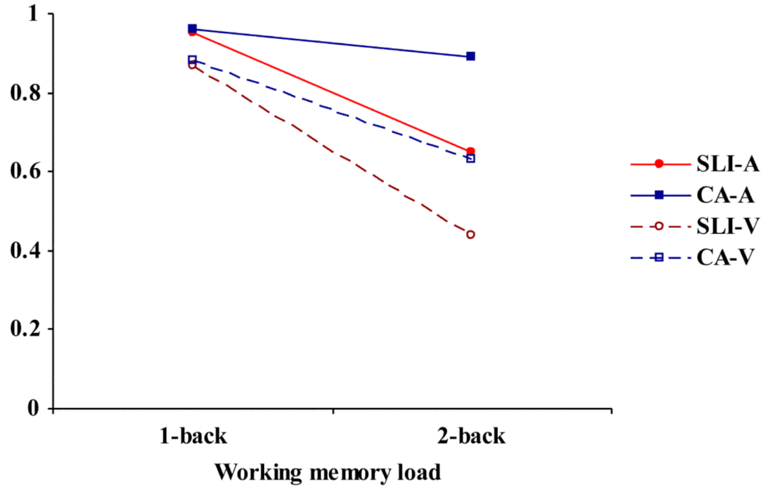

Figure 1.

Accuracy (Pr values) for children with Specific Language Impairments (SLI) and Chronologically age-matched (CA) groups for the LOW and HIGH memory load tasks.

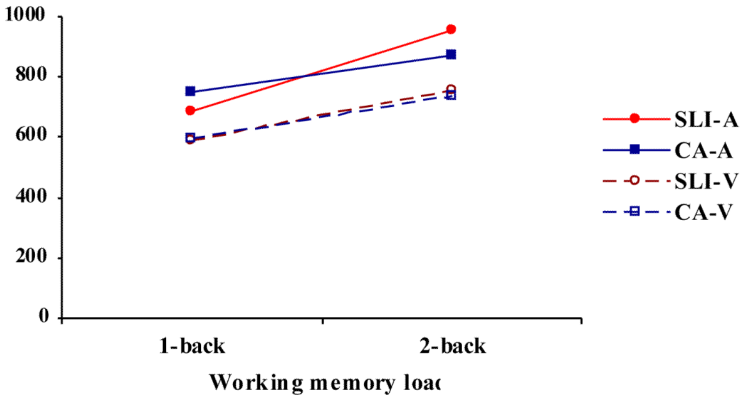

Figure 2.

Reaction times (msec) for children with Specific Language Impairments (SLI) and Chronologically age-matched (CA) groups for the LOW and HIGH memory load tasks.

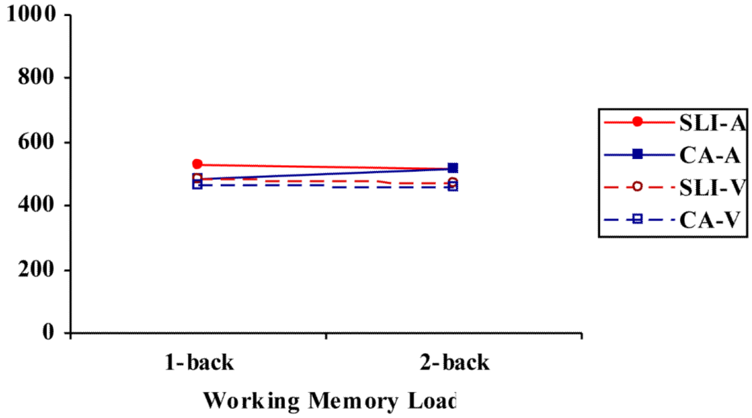

Figure 3.

P3b peak latency (msec) for children with Specific Language Impairments (SLI) and Chronologically age-matched (CA) groups for the LOW and HIGH memory load tasks.

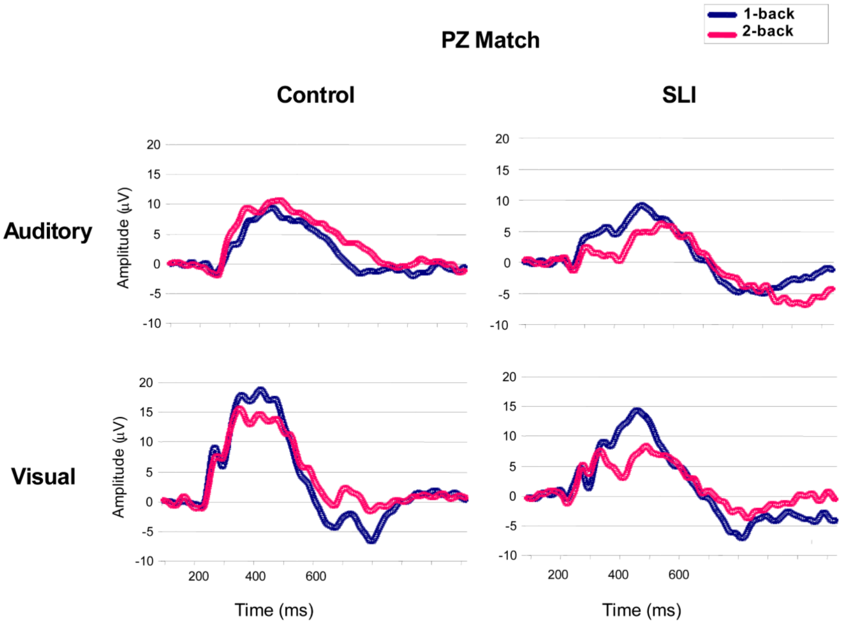

Figure 4.
Grand-average event-related potentials for correct trials in the auditory and visual modalities for the children with Specific Language Impairments (SLI) and Chronologically age-matched (CA) groups at midline parietal (Pz) sites for match conditions.

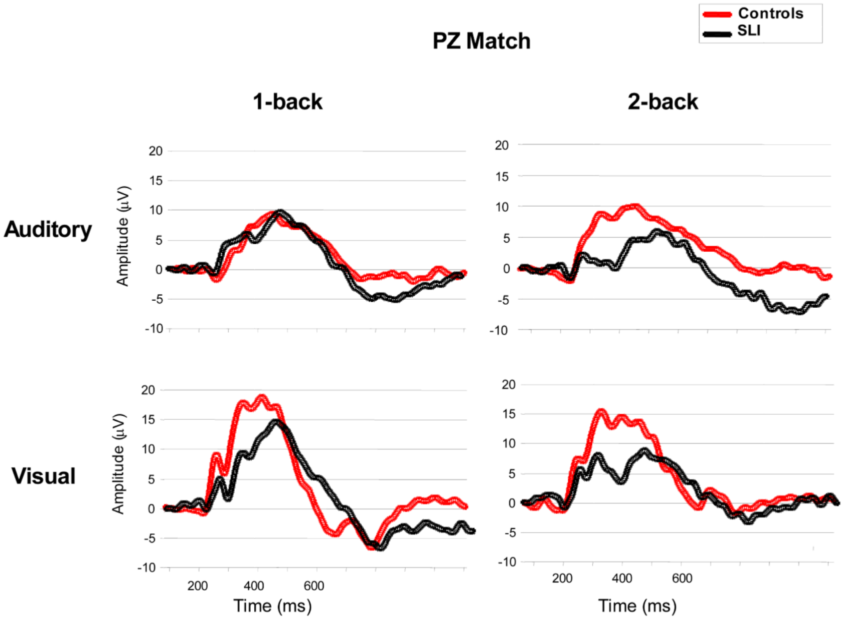

Figure 5.

Grand-average event-related potentials for auditory and visual modalities for correct trials at midline parietal (Pz) sites for match conditions for children with Specific Language Impairments (SLI) and Chronologically age-matched (CA) peers.

Table 1

Age and standardized scores for language assessment measures for the SLI and the CA groups.

	SLI (N=10)			CA (N=10)			Comparison	
	Mean	**SD**	**Range**	**Mean**	**SD**	**Range**	***t(18)***	***p***
Age in months	156	13	141 – 178	152	12	142 – 176		
IQ [1]	100	14	83 – 129	113	11	98 – 129	2.31	< .05*
ELS[2]	72	7	64 – 80	103	13	88 – 134	6.37	< .001*
OD[3]	5	2	3 – 9	13	2	8 – 15	7.43	< .001*
NRT[4]	72	11	56-85	91	3	85-96	21.0	< .001*

[1] Nonverbal I.Q. (Columbia Mental Maturity Scale or Leiter International brief IQ), (Burgemeister *et al*., 1972; Roid & Miller, 1997) Age-scaled scores have means of 100, SD 15.

[2] Expressive Language score Clinical Evaluation of Language Fundamentals – Revised (CELF-R, Semel *et al*., 1987) Age-scaled scores have means 100, SD 15.

[3] Oral Direction Subtest score, Clinical Evaluation of Language Fundamentals – Revised (CELF-R, Semel *et al*., 1987) Age-scaled scores for individual subtests have means 10, SD 3

[4] NonWord Repetition; Total Phonemes Produced (Dollaghan & Campbell, 1998)

Table 2

Mean Midline P3b peak amplitude (microvolts) in the Auditory modality for the SLI and CA groups.

		Match		
	***n*-back**	**Frontal**	**Central**	**Parietal**
SLI	1-	.49 (5)	4.2 (4)	9.2 (3)
	2-	−.42 (4)	3.0 (5)	6.4 (3)
CA	1-	−2.0 (7)	5.7 (4)	13.7 (6)
	2-	−1.8 (4)	5.5 (5)	14.1 (6)

Table 3

Accuracy, reaction time, and P3b peak latency for matches in the auditory modality for the SLI and CA groups.

		Match		
	***n*-back**	**RT (ms)**	**Accuracy (% correct)**	**P3b Latency Pz (ms)**
SLI	1-	685	99 (1)	530 (21)
	2-	952	86 (7)	516 (21)
CA	1-	746	99 (1)	486 (45)
	2-	874	96 (3)	515 (35)

Table 4

Mean Midline P3b peak amplitude (microvolts) in the Auditory modality for the SLI and CA groups.

			Match	
	***n*-back**	**Frontal**	**Central**	**Parietal**
SLI	1-	−1.5 (6)	7.4 (7)	15.8 (9)
	2-	−2.7 (3)	3.1 (4)	9.3 (6)
CA	1-	.97 (7)	11.8 (12)	21.8 (10)
	2-	2.0 (7)	12.3 (8)	19.5 (9)

Table 5

Accuracy, reaction time, and P3b peak latency for matches in the visual modality for the SLI and CA groups.

		Match		
	***n*-back**	**RT (ms)**	**Accuracy (% correct)**	**P3b Latency Pz (ms)**
SLI	1-	595	95 (3)	482 (36)
	2-	754	80 (11)	473 (39)
CA	1-	593	96 (4)	468 (33)
	2-	738	87 (8)	459 (27)