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Electrophysiological dissociation between verbal and nonverbal semantic processing in learning disabled adults

Elena Plante [a,b,*], Cyma Van Petten [b,c], Ava J. Senkfor [c]

[a] Department of Speech and Hearing Sciences, The University of Arizona, P.O. Box P.O. Box 210071Tucson, AZ 85721-0071, USA
[b] National Center for Neurogenic Communication Disorders, The University of Arizona,, Tucson, AZ 85721, USA
[c] Department of Psychology, The University of Arizona, Tucson, AZ 85721, USA

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Abstract

Event-related potentials (ERPs) were recorded as 16 adults with learning disabilities (LD) and 16 controls were presented with two sets of stimuli. The first set comprised pairs of line drawings and environmental sounds (nonverbal condition); the second consisted of printed and spoken words (verbal condition). In the controls, semantically related items elicited smaller N400s than unrelated items in both conditions, with opposing hemispheric asymmetries for spoken words and environmental sounds. The LD group did not show a significant difference between related and unrelated words, despite a robust context effect for nonspeech sounds. The results suggest anomalous processing limited to the verbal domain in a simple semantic association task in the LD group. Semantic deficits in this group may reflect a relatively specific deficit in forming verbal associations rather than a more general difficulty that spans both verbal and nonverbal domains. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Vocabulary deficits can be found routinely in association with learning disabilities,[1] both in children [19,26,27,51,54,59,65,70,78] and in adults [2,47,48,53,67]. Several explanations are available to account for the presence of vocabulary deficits. One focuses on the role of reading in building vocabulary through the school years. This account posits that poor phonological decoding skills in this population leave few resources available to move beyond phonetic decoding to semantic decoding. Although this "limited resources" account may have merit, it is not clear that children would be competent in making the semantic associations if phonological decoding were not an issue. In fact, a few studies that have examined vocabulary learning in students with learning disabilities suggest that their problems are not solely tied to reading proficiency [27,55,59,79]. Others have demonstrated that vocabulary is itself predictive of reading comprehension [3,8,70], suggesting that vocabulary deficits contribute to, and therefore may predate academic difficulty.

Insight into the roots of vocabulary deficits can be gained by examining vocabulary skills prior to the school years. Although a learning disability is not typically diagnosed before a child enters school, children with specific language impairment, whose weak language skills place them at high risk for later learning disabilities, are readily diagnosed during the preschool years. Several studies have looked at both vocabulary levels and vocabulary learning in these children. Group differences can be found between language-impaired and normally developing children on a range of single-word vocabulary measures (e.g., [5,25]). However, the

* Corresponding author. Fax: +1-520-6219901.
E-mail address: eplante@u.arizona.edu (E. Plante).

[1] Under the federal law governing services to school-age children with specific learning disability in the United States, this disorder is defined as involving a deficit in one or more of the components of language, which negatively impacts academic performance including listening, speaking, reading, and writing. The diagnosis excludes other handicapping conditions including mental retardation and frank sensory, motor, or emotional disorders. As such, a designation of a learning disability is closely related to and overlaps with other diagnostic categories including developmental dyslexia and specific language impairment.

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scores of language impaired and normal children overlap sufficiently that the diagnostic use of vocabulary tests leads to under-identification of language-impaired preschoolers [25]. Similar variability has emerged when vocabulary acquisition has been studied. Several investigations have found significant group differences in the number of trials needed for children with normal and impaired language to comprehend or use new lexical items. However, a subset of the language-impaired children in these studies performed within the range of their normal peers [15,24,34,63].

Group differences between language-impaired and normal children can be found at the earliest stages of lexical acquisition. Several studies have examined children's initial mapping of lexical items to real-world experience using *fast mapping* or *quick incidental learning* paradigms. Such paradigms involve the ability to rapidly associate semantic information (e.g., objects, actions, attributes) with a verbal label, given limited exposure to both. In a typical fast mapping experiment for object/noun relationships, a child may engage in play with one or more unfamiliar objects. During the session, the experimenter will refer to each object with a novel word a limited number of times (e.g., "Let's measure the koba. We can count these to see how long the koba is. We can put the koba away now") [45]. Even 3 and 4-year-old children prove able to remember the relationship between object and label weeks later. Fast-mapping laboratory paradigms are thus designed to be analogous to natural vocabulary acquisition in the real world. A series of studies which examined fast mapping in preschool language-impaired children who had vocabulary deficits [61–63] found deficits as compared to control children. Additional studies have found marginal or no group differences when low vocabulary was not used as a subject selection criterion [10,24].

Several variables have been investigated for their role in facilitating or inhibiting vocabulary acquisition in children with specific language impairment. Phonological complexity is known to influence word learning in both normal children [22,23] and in children with facial anomalies that affect their speech production [16]. However, in one study that examined the role of this variable in children with specific language impairment, no difference was found in the rate of acquisition for phonologically simple versus complex words in a supported learning context [24]. Likewise, the salience of a new word label within the speech stream had no significant effect on fast mapping [63]. Nouns appeared easier to learn than verbs in one study [63], but the source of this difference remains unknown. Two possibilities are that the syntactic role of verbs or the transient nature of their semantic referents may have made them more difficult to learn. In a separate study, the semantic familiarity of the referent did facilitate learning of object names by normally-developing children, but conferred no advantage for children with language impairment [24]. Interestingly, although Gray found that children's success in fast mapping is related to the rate at which they acquire new (natural) vocabulary, variation in the single-word vocabulary test scores does not seem to predict success in fast mapping [24,34,60].

In summary, vocabulary deficits are common among both children and adults identified as having either language impairments or learning disabilities, although individual variability has been noted both within and between studies. When vocabulary deficits occur, the source of these deficits remains poorly understood. Of the variables known to be related to vocabulary learning, particularly at its earliest stages, the ability to form a semantically-based association between referents and their labels seems to be impaired in language-impaired children. This is consistent with Swanson's [69] theory that individuals with learning disabilities have particular problems in forming associations between verbal (lexical items) and nonverbal information (pictures). However, it should be noted that both Swanson's memory paradigms and the typical *fast mapping* paradigms confound cross-modal mappings (e.g., visual/auditory) with cross-domain mappings (e.g., verbal/nonverbal) by evaluating associations between spoken words and visual scenes. It is not yet clear whether the difficulties that language- and learning-disabled subjects experience in forming associations are due to cross-modal relationships, cross-domain relationships, or the mere presence of verbal stimuli. In this regard, it is important to consider that for older children and adults, vocabulary acquisition often relies heavily on linguistic context. For instance, new words can be acquired while reading, in the absence of physically present referents.

In order to elucidate this issue, we contrast semantically related and unrelated stimuli in the verbal and nonverbal domains. Specifically, we examine modulations of brain electrical activity induced by semantic relationships as a function of whether the stimuli are cross-modal pairs of words (print/speech) or nonverbal pairs composed of line drawings and environmental sounds. Our primary dependent measure is a late component of the event-related potential (ERP), the N400.

2. ERP measures of semantic processing

Event-related potentials recorded from the scalp reflect summed synaptic activity that is timelocked to stimulus presentation or a motor response. The component of the ERP which has been most closely tied to language processing is a late negative wave peaking at about 400 ms poststimulus onset, the N400 (see [40,73]). When pairs or lists of words are presented visually, the amplitude of the N400 is smaller if the eliciting word is semantically related rather than unrelated to the preceding word. For words in sentences, N400 amplitude is determined by the degree of contextual constraint imposed by the preceding portion of the sentence; highly predictable final words elicit smaller N400s than congruent but unlikely words, which in turn elicit smaller N400s than completely anomalous final words. Sentence-intermediate words elicit N400s of graded amplitude depending on their position within the sentence: early words elicit relatively larger N400s than later words as the later words can benefit from a larger amount of preceding context. Despite large differences in the earlier sensory components of the ERP, auditory words and signs in American Sign Language yield similar semantic context effects to those observed for printed words [57,76]. The N400 semantic context effect is thus relatively independent of sensory modality for linguistic input. Several psycholinguistic accounts of how semantic context influences word processing have been proposed, with little general consensus; the same is true of research using N400 measures of semantic processing (e.g., [6,74]).

N400 context effects have also been observed for nonverbal but meaningful stimuli, albeit with somewhat different scalp distributions than for words. When line drawings are preceded by either printed sentences or other line drawings, the difference between semantically related and unrelated drawings is similar to the linguistic N400 in wave shape and latency, but somewhat larger at anterior scalp sites [21,30]. Meaningful nonspeech sounds such as those used in the present study elicit smaller late negative potentials when preceded by related than unrelated spoken words, but with a different hemispheric asymmetry than observed for words [75]. For convenience, we shall refer to these context effects on nonverbal stimuli as N400 effects. However, the differing scalp distributions of the context effects for words versus nonverbal stimuli suggest the engagement of different (although possibly overlapping) populations of neurons in processing their meanings. Intracranial recordings in epilepsy patients undergoing presurgical evaluation have shown locally generated N400-like responses to words in both medial and lateral regions of the temporal lobe [14,58,66], but conceptual processing of meaningful nonverbal stimuli has not been evaluated with this technique.

3. ERP studies of developmental learning disability and language impairment

Despite extensive use of the N400 as an index of semantic processing during normal language processing, ERP studies of comprehension in developmental language- or learning-disabled populations have been limited. A larger number of studies have investigated auditory sensory processes in language impaired or learning disabled subjects using tones, clicks, or syllables as stimuli. These have yielded mixed reports of reduced amplitudes, increased latencies, or altered hemispheric asymmetries in the P1 and N1 components, which sometimes depend on the exact nature of the deficits apparent in various perceptual/cognitive test batteries (see [43] for review). A more consistent abnormality has been a reduction in the amplitude of the mismatch negativity generated by auditory cortex in response to a change in a sequence of repetitive stimuli, although it is not yet clear if this is true for all auditory stimuli or only for speech sounds [31,32,64].

Another set of studies have compared normal and language-impaired or learning-disabled populations in "oddball" paradigms to investigate a later cognitive potential which is dependent on task-relevant classification of stimuli rather than on sensory processing. These have documented latency delays and/or reduced amplitudes of the P3 response to infrequent stimuli with both visual and auditory presentation, and across verbal and nonverbal stimuli (for recent studies, see [12,44]; for review of older studies see [71]). P3 amplitudes and latencies are sensitive to the cognitive effort and time required to evaluate and classify stimuli, so that these findings are indicative of dysfunction, but may not discriminate language or learning disability from a variety of neurological and psychiatric disorders which also lead to P3 deficits (see [39] for review).

Most relevant to the present experiment are six recent studies that used related/unrelated stimuli in paradigms designed to modulate N400 amplitude. McPherson, Ackerman and colleagues have consistently reported that words or drawings preceded by a rhyming stimulus fail to elicit smaller N400s than nonrhyming stimuli in dysphonetic dyslexic subjects, unlike control subjects [1,49,50]. Manipulations of semantic context have yielded more variable results. Stelmack and Miles [68] reported that learning-disabled subjects who were deficient in reading and spelling showed smaller N400s for printed words following related than unrelated line drawings (the normal result), but that this context effect showed a more anterior scalp distribution than in control subjects. Miles and Stelmack [52] report a more dramatic group difference in that LD subjects with reading and spelling deficiencies failed to show a significant N400 semantic context effect for printed words preceded by either drawings or spoken words. In contrast to these experiments using paired stimuli, Neville and colleagues used simple visual sentences ending with semantically congruous or anomalous words. For mid-sentence words, language-impaired subjects showed larger N400s than did control subjects, as might be expected if the impaired subjects failed to utilize the semantic context provided by an ongoing sentence. However, at final word positions, the impaired subjects

Table 1
Test scores for participants of experiment 1[a]

	LD group		Control group			
	Mean	SD	Mean	SD	t-test	P
PPVT-R	96.4	0.5	111.2	11.1	3.99	<0.01
Modified token test	76%	10%	88%	8%	3.77	<0.01
Reading span	2.3	0.5	2.5	0.5	0.84	n.s.

[a] Note: PPVT-R scores provided as standard scores (mean = 100; SD = 15). Modified token test scores provided as percent correct. Reading span scores provided as level scores.

demonstrated larger N400 differences between congruous and anomalous words than did the controls [56]. The authors suggest that this enhanced semantic context effect raised the possibility that "…the auditory and visual sensory processing deficits and the syntactic processing deficits evidenced by all or some of the LI/RD children lead to… greater reliance on context for word recognition than in control subjects" [56].

The reason for these differential results of both reduced and enhanced N400 semantic context effects in LD subjects is not clear. One ever-possible account is simply that the two laboratories tapped different subgroups within a heterogeneous disorder, although this is not obvious from comparing the selection criteria of the three studies. A second possibility is that the sentence stimuli of Neville et al were more successful in encouraging attentive reading (and thus attention to meaning) than Stelmack and Miles' paired stimuli. In any case, the database is yet sparse and worthy of further research.

4. The present study

The present paradigm uses paired stimuli, but in the context of a task which demands attention to both members of each pair. One novel aspect of the paradigm is the use of both verbal and nonverbal stimuli, which may reveal differences between conceptual relationships within and outside of language. In either case, the ability to distinguish between semantically related and unrelated stimulus pairs should be reflected by differences in N400 amplitude. If semantic processing is compromised in the verbal, but not in the nonverbal domain, then we may observe reduced amplitudes, delayed latencies, or unusual scalp distributions in the LD group for the verbal condition only. Alternatively, we may observe a more general abnormality that spans both verbal and nonverbal domains.

A second novel aspect is the inclusion of adult LD subjects who are functioning well enough to attend college. This population represents the milder end of the learning disabilities spectrum. However, any processing difference found in an adult population is likely to reflect long-term and stable characteristics of the disorder. Observations from this population may thus shed light on the outcomes of developmental learning disabilities.

4.1. Experiment 1

4.1.1. Method

4.1.1.1. Participants. Thirty-two college students participated in this study. Sixteen students (five males, 11 females) comprised the learning disabilities (LD) group. These were students who identified themselves as having a learning disability or dyslexia and were receiving support services through a university-based program for students identified with standardized testing (i.e., a Weschler Intelligence Scale test [80,81] and the Woodcock–Johnson Psycho-Educational Battery [82]). Their mean age was 23 years (range 18–34 years). The second group (the control group) included 16 students (five males, 11 females) who lacked a personal or family history for language impairment, learning disability, or dyslexia by self-report. Their mean age was 22 years (range 18–36 years). Fifteen of the participants in each group were undergraduates and one was a graduate student; thirteen in each group were right-handed and three were ambidextrous or left-handed. All participants were screened for frank neurological dysfunction (e.g., head injury, seizure disorder) and one potential participant was excluded on this basis.

For descriptive purposes, the participants were administered a brief battery of tests. The results of these are reported in Table 1. The Peabody Picture Vocabulary Test—Revised (PPVT-R) [13] was selected because the experiment concerns word-level semantic processing. A modified version of the Token Test (Modified Token, [53]) was used to determine the degree to which subject groups differed on an alternate measure of language processing. This modification of the standard Token Test uses longer and more complex directions than standard versions of the Token Test in order to detect subtle syntactic processing deficits. It is known to be sensitive to long term deficits in adults who received language therapy as children [72]. Finally the reading span measure [9] was administered because previous work has demonstrated that, at least in sentence processing paradigms, N400 amplitude can vary as a function of working memory capacity as measured by this task [77]. This working memory measure requires the subject to read a series of sentences aloud. Following each set of sentences, the subject is asked to provide the last word of each sentence. The reading span [9] stimuli begin with sets of two sentences; we added "sets" consisting of only a single sentence to ensure that the LD subjects would achieve success at the beginning of the test. After this single-sentence block, participants proceeded to the standard block of two sentence sets, followed by a block of three sentence sets, etc., until they reached the criterion for discontinuing the task. Table 1 shows that the LD group scored lower than the control group on the vocabulary and Token Test, but not on the reading span task.

4.1.1.2. Materials and stimulus presentation. The ERP experiment consisted of two parts: a verbal block consisting of word pairs, and a nonverbal block consisting of picture–sound pairs. Two sets of 88 related pairs of items were developed. The word pairs consisted of concrete nouns shown in Appendix A, the first printed and the second spoken. Frequency of usage averaged 64 (SE 13) for the visually-presented words, and 57 (SE 5) for the auditory words (summed frequency of all regular inflections [17]). Visual words averaged 5.3 characters (SE 0.2); spoken words averaged 514 ms in duration (SE 12).

Non-language pairs consisted of simple line drawings of objects, animals or people, followed by related sounds (e.g., pictures of an ambulance, bird, and boy with mouth open, followed by a siren, birdsong, or yawning respectively). Drawings averaged 4.2 degrees of visual angle in both the horizontal and vertical dimensions. Sounds were 1500 ms in duration. Previous work showed that the environmental sounds were readily identifiable by normal listeners [75].

Auditory words were spoken by a male voice, recorded onto analogue tape, lowpass filtered at 9 kHz, and digitized at a sampling rate of 20 kHz. The audio files were edited to ensure good synchronization between the beginning of the file and the acoustic onset of the word. Identical procedures were used for the environmental sounds. During the experiment, words and sounds were presented via an audio monitor approx. 3 feet in front of the subject; volume levels were set to the comfort of each subject at the beginning of the session.

Each subject received 44 related pairs in both the word and non-language blocks, and 44 unrelated pairs formed by re-arranging the original related versions (so that the ambulance drawing might be followed by birdsong). Separate stimulus lists were formed so that each second item served equally often as a related and an unrelated stimulus across subjects.

Each pair of stimuli was followed by a probe recognition stimulus designed to ensure attentive processing. The probes consisted of fragments of one of the paired stimuli. For the word pairs, these consisted of a single letter to be matched with the visual word of the preceding pair, or a brief fragment of a spoken word (175 ms average duration) to be matched with the auditory word of the preceding pair. Similarly, picture/sound pairs were followed by either picture fragments or sound fragments. Each trial was equally likely to be followed by a visual or an auditory probe (unpredictably). Half of the probes formed a match with one of the preceding stimuli; half did not. Matching and mismatching probe stimuli were equally likely to follow related and unrelated stimulus pairs, so that the correct probe decision (present vs absent) was uncorrelated with the semantic relationship of the pairs.

During the nonlanguage block, each trial began with the appearance of a visual frame on the video monitor for 1000 ms, followed by presentation of a line drawing within the frame for 250 ms. Stimulus-onset-asychrony (SOA) from the drawing to the environmental sound was 2500 ms. After the sound, subjects received a warning stimulus indicating whether the upcoming probe would be auditory (the letter "A" appearing on the video monitor) or visual (a small visual frame). SOA between the environmental sound and the warning stimulus was 2500 ms; the warning stimulus lasted 1000 ms and was immediately followed by a picture fragment or sound fragment probe. The next trial began 5 s later. SOAs between adjacent stimuli were identical during the word block, as were the durations of the visual stimuli; durations of the spoken words were however briefer than those of the environmental sounds as described above.

Participants were seated in a reclining chair within an electrically-shielded booth. They faced the computer monitor and speaker. Buttons for 'yes' and 'no' responses to the probe recognition stimuli were positioned under the index fingers of each hand, with the hands corresponding to 'yes' and 'no' counterbalanced across subjects. The task was explained to the subject and a practice session was conducted until the subject was responding reliably and recording epochs were obtained that were artifact free. The participants then received the nonverbal condition. This condition was always given first because of the high probability of participants would use a verbal encoding strategy during this task if they had first completed the verbal task. Participants were given a short rest break after the nonverbal task and then were given the verbal task. The entire session averaged 2 h, including electrode application, rest breaks, and behavioral testing.

4.1.1.3. Electrophysiologic methods. The electroencephalogram (EEG) was recorded from 11 scalp sites

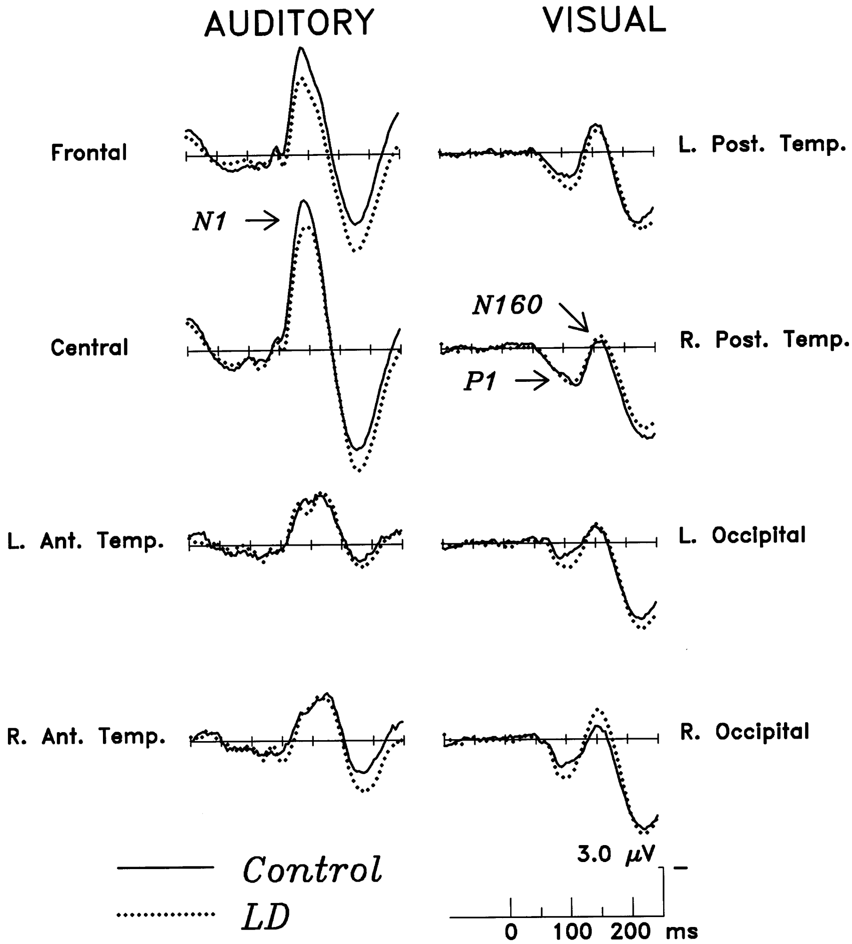

Fig. 1. Grand average ERPs elicited by all auditory and all visual stimuli in the control and learning-disabled groups (first and second members of the paired stimuli, and probe stimuli). ERPs are shown from Fz (Frontal), Cz (Central), T3 (L. Ant. Temp.) and T4 (R. Ant. Temp.) for auditory stimuli, and T5 (L. Post. Temp.), T6 (R. Post. Temp.), O1 (L. Occipital) and O2 (R. Occipital) for visual stimuli.

including midline central (CZ), parietal (PZ), and occipital (OZ) locations, along with lateral positions (F7, F8, T3, T4, T5, T6, O1, O2) as defined by the 10–20 system. These electrodes were referenced to an off-line average of the right and left mastoids. Vertical eye movements and blinks were monitored with an electrode placed below the right eye, referred to the left mastoid. Eye movements in the horizontal direction were monitored with a right-to-left bipolar montage placed at the external canthi.

The EEG was amplified by a Grass Model 12 polygraph (Grass Instruments, West Warwick, RI) with a half-amplitude cutoffs of 0.01 and 100 Hz and digitized on-line at a sampling rate of 170 Hz. Both the stimulus codes and digitized EEG were stored on optical disk for subsequent averaging. Trials with artifacts (e.g., eye movements or blinks, muscle artifact, amplifier saturation) were rejected before averaging. Responses to the second stimuli of each pair (i.e., the sound in the nonverbal set; the spoken word in the verbal set) were averaged to include a 100 ms prestimulus baseline and 950 ms of poststimulus activity.

4.2. Results

4.2.1. Sensory components of the ERP

The experimental conditions were designed to modulate a late cognitive component of the ERP, the N400. However, both auditory and visual stimuli also elicit earlier ERP components which are driven by sensory parameters of stimuli (larger for louder or brighter stimuli), and which are additionally sensitive to selective attention (larger for attended than unattended items, see [29] for review). With the recording parameters used here, these include the auditory N1 and the visual P1 and N160. Some previous studies have reported altered amplitudes, latencies, or hemispheric asymmetries of these components in developmental disorders (see [43] for review). We examined these early components after collapsing across all stimuli in a given modality to obtain measurements of these small amplitude components with the best signal-to-noise ratio possible (a minimum of 130 trials per subject per modality after averaging both the paired stimuli and the probe recognition targets). Fig. 1 shows little to no differences between the control and LD subjects in these components.

The auditory N1 was measured as the most negative peak in a latency window of 50–150 ms poststimulus onset, at the midline (Fz, Cz, Pz) and lateral (F7, F8, T3, T4, P3, P4) sites where it is most reliably recorded. The visual P1 and N160 were similarly measured at posterior sites T5, T6, O1 and O2, as the most positive peak between 50 and 150 ms, and most negative peak between 100 and 300 ms, respectively. Both the auditory N1 and the visual N160 were significantly larger over the left than right hemisphere (main effect of laterality for auditory N1: $F(1, 30) = 6.51$, $P < 0.02$; temporal/occipital x laterality for visual N160: $F(1, 30) = 5.15$, $P < 0.05$). These laterality effects did not interact with subject group, nor were any of the main effects or interactions involving group significant for amplitudes or latencies of any of the three sensory components (all Fs < 1).

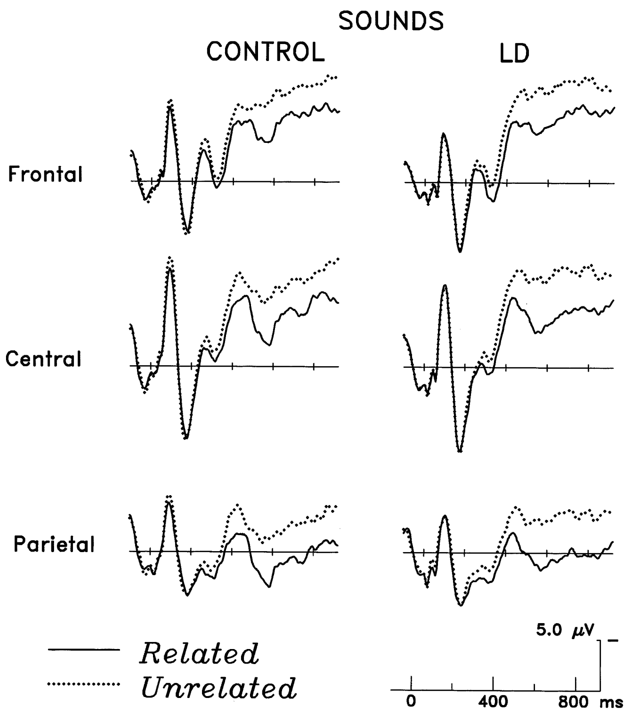

Fig. 2. Grand average ERPs from the three midline electrode sites (Fz, Cz, Pz).

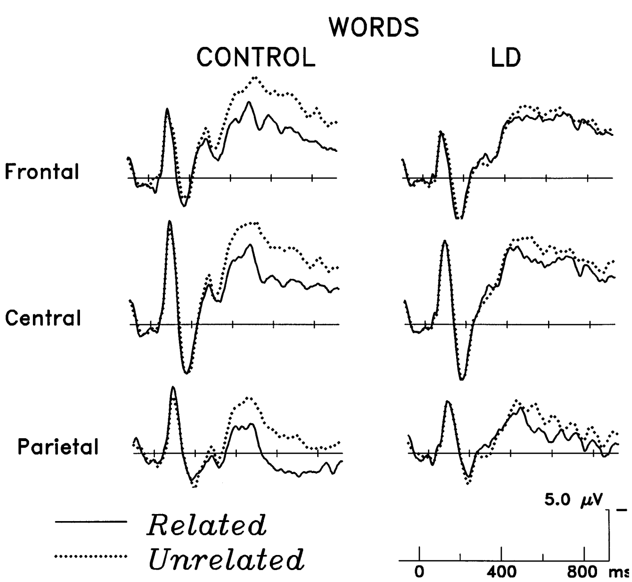

Fig. 3. Grand average ERPs from the three midline electrode sites (Fz, Cz, Pz).

4.2.2. Semantic context effects

Fig. 2 shows the ERPs elicited by the related and unrelated environmental sounds for the two groups. The auditory ERPs were characterized by an N1 peaking at about 100 ms poststimulus onset, P2 at about 180 ms, and N2 at about 300 ms. These potentials did not differ between groups for either the sound or the word stimuli. The late portion of the waveform was marked by a broad negativity that was smaller in amplitude for sounds following related than unrelated drawings, beginning around 250 ms poststimulus onset and continuing for the remainder of the recording epoch. Both controls and LDs showed a robust context effect for the picture/sound pairs. The late negativity was quantified as mean amplitude from 250 to 750 ms, relative to the 100 ms prestimulus baseline. For the midline scalp sites, an ANOVA using Group, Relationship, and Site (Fz, Cz, Pz) yielded a main effect of Relationship ($F(1, 30) = 27.7$, $P < 0.0001$) with no main effect or interactions involving Group (Group × Relationship, $F < 1$). Analysis of the 10 lateral electrodes using Group, Relationship, Anterior-to-Posterior scalp location (AP, five levels) and Left/Right similarly yielded a main effect of relationship ($F(1, 30) = 31.3$, $P < 0.0001$) with no interactions involving Group (Fs < 1).

Fig. 3 contrasts the ERPs elicited by spoken words following related or unrelated printed words in the two groups. In contrast to the similar context effects for drawing/sound pairs, the LD group exhibited a much smaller context effect for words than did the controls. The data were analyzed as above. The midline ANOVA yielded a main effect of Relationship ($F(1, 30) = 27.7$, $P < 0.0001$), accompanied by a significant Group by Relationship interaction ($F(1, 30) = 6.79$, $P < 0.02$). Analyses of the lateral sites yielded the same results (Relationship: $F(1, 30) = 14.2$, $P < 0.002$; Group × Relationship: $F(1, 30) = 5.19$, $P < 0.05$).

Although Fig. 3 displays a small context effect for spoken words within the LD group, a separate analysis of the LD data revealed that this was not statistically significant at either the midline ($F(1, 15) = 1.69$) or the lateral scalp sites ($F(1, 15) = 1.28$). The grand averages

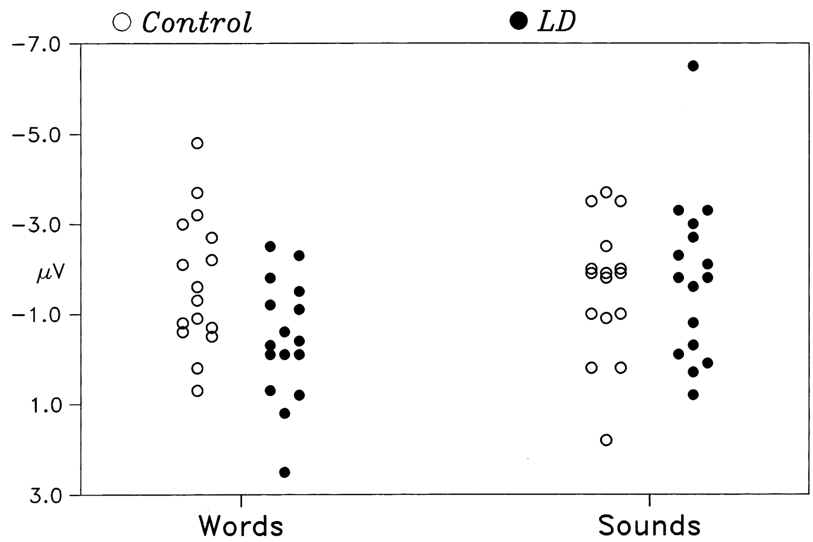

Fig. 4. Amplitudes of the differences between unrelated and related items, with each dot representing an individual subject. Negative amplitudes indicate larger N400s for unrelated than related items. Differences calculated from mean amplitudes across 250–750 ms poststimulus onset, collapsed across all scalp sites.

displayed in Figs. 2 and 3 reflect some degree of individual variability in the amplitudes of the context effects within both groups. Fig. 4 shows the amplitudes of the context effects for individual subjects, collapsed across all of the scalp sites. For spoken words, there is clearly overlap between the normal and LD ranges of variability, but the LD distribution is below the control distribution and centered near 0 uV (no context effect). In contrast, the distributions of context effects for sounds largely overlap for the two groups, with the exception of one LD subject with a particularly large context effect for sounds.

4.2.2.1. Topographic patterns of the context effects. The preceding analyses report the presence or absence of context effects, but their spatial distributions across the scalp are also of some interest. Different scalp distributions of the context effects for words versus sounds, or between groups of subjects would indicate the engagement of different (though possibily overlapping) populations of neurons. Fig. 5 displays the topography of the context effects along the anterior/posterior axis of the scalp (collapsing across left and right). When context effects were present — for both words and sounds in the control group, for sounds in the LD group — they showed similar maxima at parietal scalp.[2] Analyses of the lateral scalp sites thus yielded no interactions between the AP scalp factor and stimulus type (words or sounds) within the control group, or between groups when only the ERPs elicited by sounds were analyzed.

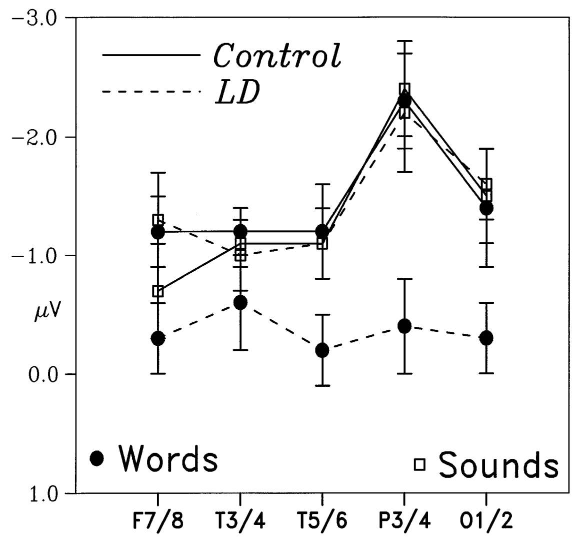

Fig. 5. Scalp distributions of the context effects in the anterior-to-posterior dimension, showing lateral scalp sites from frontal (F7 and F8) to occipital (O1 and O2). Context effects calculated as the difference between unrelated and related items, from 250–750 ms poststimulus onset. Error bars indicate the standard error of the mean.

[2] The pair of parietal sites (P3, P4) were compared to each of the other lateral scalp pairs (frontal F7 and F8, anterior temporal T3 and T4, posterior temporal T5 and T6, occipital O1 and O2) in a series of ANOVAs taking Relationship (related vs unrelated), Site (parietal vs other), and Left/Right as factors. For the sounds in the control group, significant interactions between Relationship and Site indicated that the related/unrelated difference was larger at parietal sites than each of the other four pairs of sites (all $Fs(1, 15) > 5.24$, all $ps < 0.05$). For sounds in the LD group, the parietal relationship effect was larger than that observed at anterior and posterior temporal sites ($Fs(1, 15) > 6.30$, $ps < 0.05$), but not significantly larger than the relationship effect at frontal or occipital sites (Fs of 1.79 and 2.14, respectively). For words in the control group, the parietal relationship effect was larger than that observed at posterior temporal and occipital sites ($Fs(1, 15) > 7.62$, $ps < 0.02$), but not signficantly larger than that observed at frontal or anterior temporal sites (Fs of 2.40 and 4.25, respectively).

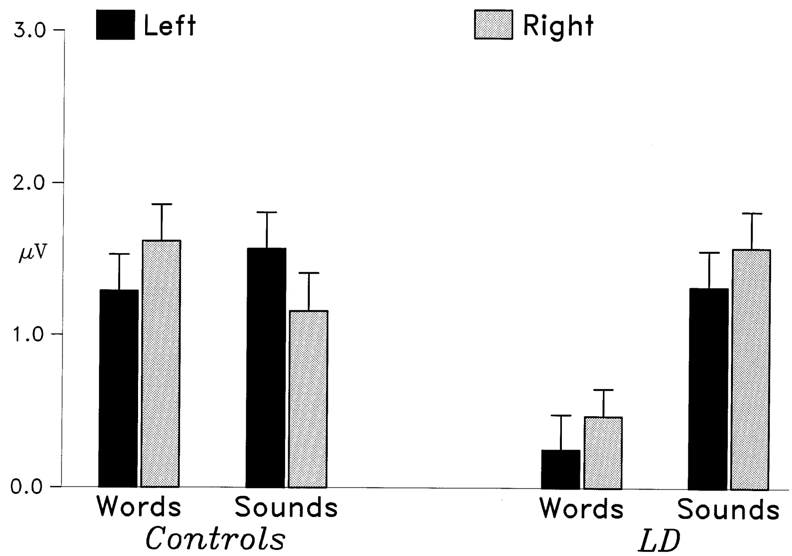

Fig. 6. Scalp distributions of the context effects recorded over the left and right scalp, collapsed across the five pairs of lateral scalp sites. Context effects calculated as the difference between unrelated and related items, from 250–750 ms poststimulus onset. Error bars indicate the standard error of the mean.

The parietal maxima of the context effects observed here is typical of N400 context effects elicited by both words and sounds in previous studies of adults [40,75].

Fig. 6 contrasts the context effects recorded over left and right scalp for the verbal and nonverbal stimuli, collapsed across the anterior-to-posterior dimension. For the control subjects, the N400 effect was somewhat larger over the right when elicited by words, but somewhat larger over the left when elicited by sounds. These opposing asymmetries within the control group yielded an interaction between Stimulus type (words or sounds), Relationship, and the Left/Right scalp factor ($F(1, 15) = 4.38$, $P = 0.05$).[3] A right-greater-than-left asymmetry for word stimuli is typical of N400 context effects [37,41]. The leftward asymmetry for context effects on environmental sounds observed here replicates our initial study using these stimuli in normal participants [75]. Within the LD group, Fig. 6 shows that the context effect for words had a slight (typical) rightward asymmetry, but the overall effect was not statistically different from zero (see above). For the sounds, the LD group also showed a small rightward asymmetry. Although this pattern of asymmetry was distinct from that of the control group, it was not independently significant when only the LD sound ERPs were analyzed, nor were the asymmetries large enough to yield a Group by Relationship by Left/Right interaction for the ERPs elicited by sounds.

[3] When the data were normalized to remove any overall amplitude differences between the ERPs elicited by words and sounds (see [46] for discussion of this statistical issue), the Stimulus type by Relationship by Left/Right interaction within the control group remained significant ($F(1, 15) = 6.0$, $p < 0.02$).

4.2.3. Probe recognition task

4.2.3.1. Performance. Table 2 shows that accuracies in matching the letter, spoken word fragment, picture fragment, and sound fragment probes to the preceding paired stimuli were generally quite high. Correct responses include both "yes" responses to matching probes, and "no" responses to mismatching probes. Accuracies were analyzed via an ANOVA using Group as a between-subject factor, with Verbal/Nonverbal and Modality (visual vs auditory) as within-subject factors. The nonverbal probes led to somewhat better performance than verbal ($F(1, 30) = 11.0$, $P < 0.005$), and auditory probes better than visual ($F(1, 30) = 6.7$, $P < 0.02$). Table 2 suggests that LD accuracies were slightly lower than controls', particularly for the letters and spoken word fragments, but these effects were evident only as statistical trends (main effect of Group: $F(1, 30) = 3.2$, $P = 0.09$; Group × Verbal/Nonverbal: $F(1, 30) = 3.5$, $P = 0.07$). However, a planned comparison of these verbal targets alone yielded a small (4.5%) but significant deficit for the LD group as compared to the controls ($F(1, 30) = 5.4$, $P < 0.05$) which was not evident for the nonverbal targets ($F < 1$).

Table 2
Accuracies in the probe recognition task

	Control	LD
Spoken word fragments	94.3 (0.6)[a]	88.1 (2.7)
Letters	90.1 (1.5)	87.3 (2.5)
Sound fragments	96.1 (0.6)	95.5 (0.9)
Picture fragments	91.4 (1.8)	90.7 (2.3)

[a] Percent correct. Standard error in parentheses.

Table 3
Reaction times in the probe recognition task

	Control	LD
Spoken word fragments		
Present	799 (59)[a]	901 (80)
Absent	884 (63)	1044 (85)
Letters		
Present	1102 (95)	1260 (106)
Absent	1222 (109)	1340 (104)
Sound fragments		
Present	762 (54)	899 (74)
Absent	860 (47)	1011 (75)
Picture fragments		
Present	1108 (76)	1113 (68)
Absent	1052 (71)	1183 (73)

[a] Means and standard errors for correct responses, in ms.

Reaction times for correct responses are shown in Table 3, and were analyzed via an ANOVA taking Group, Verbal/Nonverbal, Modality, and Present/Absent as factors. Verbal probes received faster responses than nonverbal ($F(1, 30) = 5.4$, $P < 0.05$), auditory faster than visual ($F(1, 30) = 83.0$, $P < 0.0001$), and 'yes' responses were faster than 'no' responses ($F(1, 30) = 11.4$, $P < 0.005$). There were no significant interactions involving Group.

4.2.3.2. ERPs. Fig. 7 shows ERPs elicited by the recognition probe stimuli, collapsed across the spoken word fragments, sound fragments, letters, and picture fragments. All of the probe stimuli elicited decision-related P3 components that were largest at parietal scalp, and larger for the matching than mismatching probes. There was little evident difference between the control and LD subjects in the probe ERPs.

Eight classes of probe stimuli (4 stimulus types × present/absent) were presented to mandate attention to both members of the paired stimuli which were central to the experimental design. There were thus too few trials of individual probe conditions (e.g., matching sound fragments) to yield adequate signal-to-noise ratios to form ERPs. However, given that the LD group showed a small accuracy deficit in classifying the verbal probes (letters and spoken word fragments), a comparison of verbal to nonverbal probes is of some interest. ERP amplitudes were measured in a 300–600 ms latency window, which covers the bulk of the match/mismatch effect, and included in ANOVAs with factors Group, Verbal/Nonverbal, Match, and electrode site as factors. At the midline electrode sites, nonverbal probes elicited more positive ERPs than verbal ($F(1, 30) = 7.71$, $P < 0.01$), and matching probes more positive than mismatching ($F(1,30) = 81.9$, $P < 0.0001$). The match/mismatch effect was largest at Pz, typical of the decision-related P300 component of the ERP (Match × Anterior/Posterior: $F(2, 60) = 13.2$, $P < 0.0001$, $e = 0.86$[4]). Analysis of the lateral electrode sites confirmed these results (main effect of verbal vs nonverbal, $F(1, 30) = 10.7$, $P < 0.005$; main effect of match vs mismatch, $F(1, 30) = 101.6$, $P < 0.0001$). The lateral analysis also included three-way interactions involving the two experimental manipulations and scalp site (Verbal/nonverbal × AP × left/right, $F(4, 120) = 4.13$, $P < 0.005$, $e = 0.95$; Match/mismatch × AP × left/right, $F(4, 120) = 4.69$, $P < 0.005$, $e = 0.73$). Fig. 7 suggests that these complex interactions can be attributed to the fact that the match/mismatch effect for verbal probes had a clear parietal focus, whereas the match/mismatch effect for nonverbal probes included a substantial frontal difference; the functional interpretation of the frontal sensitivity to probe type is unclear. For present purposes, the most central outcome of the probe ERP analyses is that there were no main effects or interactions involving subject group in analyses of the midline or lateral sites.

Peak latency of the P300 was measured at Pz where this component was largest, and analyzed as above. Neither group nor any of the probe type manipulations influenced P300 latency.

4.3. Experiment 2

4.3.1. Methods

4.3.1.1. Participants. The results of experiment 1 led us to question whether the LD participants could distinguish related from unrelated pairs of words. We attempted to contact all of the participants to obtain explicit semantic judgements about the stimuli. Twelve (four male, eight female) of the 16 LD participants, and 10 of 16 (four male, six female) controls returned for additional testing conducted a minimum of 7 days and a maximum of 1 year after their initial ERP session.

4.3.1.2. Materials and procedures. Each individual received the alternate stimulus list not experienced during experiment 1 (e.g., if "apple/orange" and "salt/leg" were presented in experiment 1, this participant now received "blouse/orange" and "arm/leg"). Each visual stimulus was presented on paper in a font size approximating that of the computer font used originally, followed by an auditory stimulus presented on tape. Interstimulus timing approximated that used during experiment 1. After each trial, participants responded "related" or "unrelated" verbally.

Participants were also asked to take additional behavioral tests in order to determine whether the variability in ERP effects noted in Study 1 were related to their behavioral characteristics. These included the Let-

[4] Huhyn–Feldt correction for nonsphericity of variance.

ter-Word Identification and Passage Comprehension subtests of the Woodcock–Johnson Psycho-Educational Battery [82]. These two subtests comprise the Broad Reading Cluster for this battery. They also received the spelling subtest of the Multilingual Aphasia Battery [4] and a test of verbal fluency in spontaneous language [72]. The verbal fluency metric involves calculation of the number of words spoken during a standardized picture description task, exclusive of words spoken as part of verbal mazes, self-corrections, or fillers. Results from the Modified Token Test, the PPVT-R, and the Reading Span measure given as part of experiment 1 were also analyzed.

4.3.2. Results

Both groups performed at near ceiling levels on both the nonverbal and verbal relationship tasks. For the nonverbal drawing/sound pairs, the median score for the LD group was 98.5% correct (range 95.3–100%), and the median score for the control group was also 98.5% (range 94.8–100%) correct. For the verbal condition, the median score for the LD group was 96.0% correct (range 87.5–97.7%) and the median score for the control group was 98.9% (range 95.5–100%) correct. The 2.9% median difference for verbal material was statistically significant (Mann–Whitney U, $z = 3.24$, $P < 0.01$), whereas the nonverbal group difference was not. However, it is important to note that most LD subjects correctly identified most word pairs as related or unrelated.

Results of the additional behavioral tests are provided in Table 4. As expected the LD group performed significantly worse than controls on the spelling and reading tests, although speaking rate did not differ between groups.

Simple (Pearson) correlations were calculated for the relationship between each behavioral test and the mean amplitudes of the two ERP context effects shown in Fig. 4. Two sets of correlations were performed, one including both control and LD participants, and a second using data from the LD participants alone. The many correlation coefficients ranged from -0.30 to 0.45; none were significant at the $P < 0.05$ level. Although the LD participants thus performed worse than

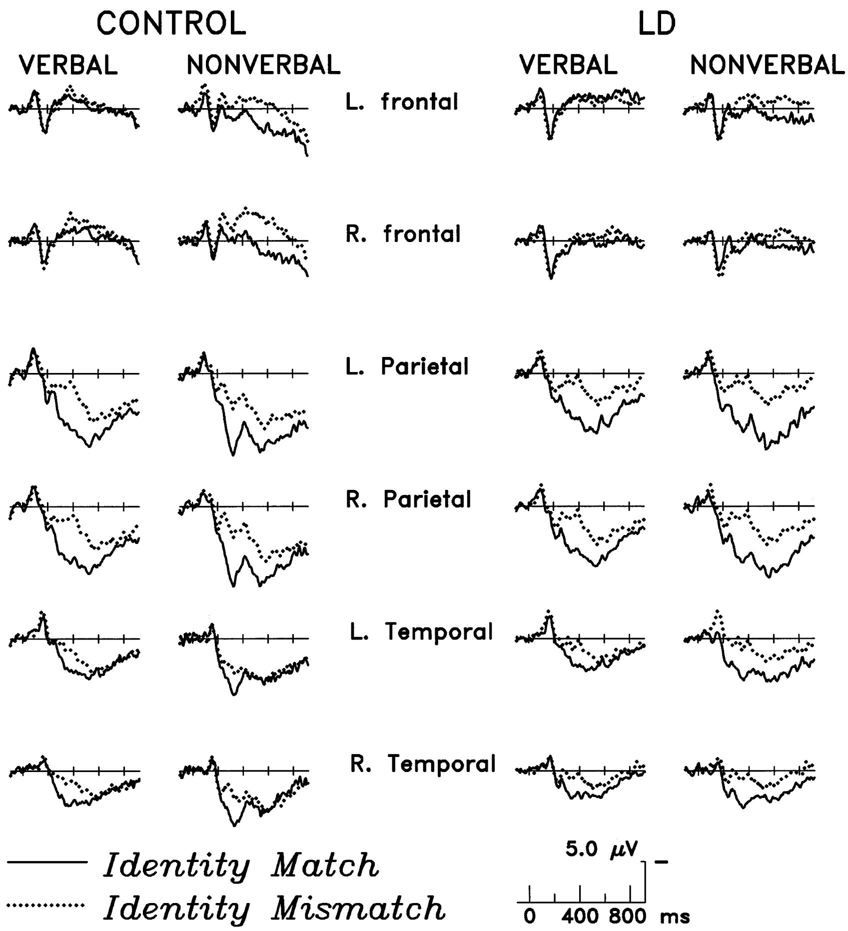

Fig. 7. Grand average ERPs elicited by the probe recognition targets which followed each pair of related or unrelated items, at F7 and F8 (left and right frontal), P3 and P4 (left and right parietal), and T5 and T6 (left and right temporal). Verbal probes were single letters and spoken word fragments, nonverbal probes were fragments of the environmental sounds or line drawings.

Table 4
Test scores for participants of experiment 2

	LD group		Control group			
	Mean	SD	Mean	SD	Test[a]	*P*
WJ—letter–word identification	106.4	12.0	124.6	16.3	3.33	<.01
WJ—passage comprehension	96.1	16.0	116.0	15.5	3.27	<.01
WJ—broad reading	101.6	11.6	122.2	15.8	3.90	<.01
MAB—spelling	92.1	9.3	98.2	5.1	2.56	<.01
Speaking rate	142.0	32.6	142.3	32.2	0.02	n.s.

[a] *t*-test used in all cases except MAB — spelling, for which a Mann–Whitney *U*-test was used. Note: WJ (Woodcock–Johnson Psychoeducational Battery) scores provided as standard scores (mean = 100; SD = 15). MAB (Multinglingual Aphasia Battery) Spelling scores provided as percent correct. Speaking rate (see [72]) in words per minute.

controls on five of the seven behavioral tests administrated, group status was more predictive of a small ERP context effect for words than was any particular test.

5. Discussion

Event-related potentials in adult learning-disabled subjects revealed a rather specific deficit: in contrast to matched controls, no N400 context effect was observed for pairs of printed and spoken words. In contrast, the same subjects showed a robust N400 context effect for the nonverbal stimulus pairs. Thus, cognitive processing within the verbal domain differed for the LD group in comparison to both the nonverbal domain and the control group. This group difference in a late cognitive component of the ERP occurred despite a lack of differences in earlier components of the auditory and visual ERPs. The auditory N1 and the visual P1 and N160 components of the LD group were normal in amplitude and latency, suggesting no gross deficits in sensory processing. P3 components elicited by target stimuli likewise had similar amplitudes, scalp distributions, and latencies in the two groups.

The verbal/nonverbal dissociation evident in N400 amplitudes for the LD group was paralleled by a more subtle distinction in the control subjects. The context effect for spoken words showed a right-greater-than-left asymmetry much like the typical result for printed words [37,41]. In contrast, it was the left side that showed the larger difference between related and unrelated environmental sounds. These opposing asymmetries confirm our previous report from normal subjects [75]. The previous report reviews the neuropsychological literature, suggesting that processing of nonspeech sounds is more dependent on the right hemisphere than is speech processing, and the idea that N400 presents a case of *paradoxical lateralization*. Paradoxical lateralization of an ERP component arises when neural activity in one hemisphere produces voltage fields larger over the opposite hemisphere due to the geometric orientation of the active neurons, and has been well described for other ERP components whose neural substrates are better characterized than those of the N400 (see [60], pp. 221–223, 403–405 for review). Studies of aphasic patients support the conclusion that the N400 context effect elicited by words is critically dependent on an intact left hemisphere despite its rightward scalp asymmetry [18,28]. The opposing asymmetries for words and sounds in the control subjects thus suggest a larger left hemisphere contribution for processing word meaning, but a larger right hemisphere contribution for interpreting nonspeech sounds. The magnitudes of the asymmetries were small however, so that the N400 effects for both words and sounds are likely to reflect bilateral activity as well. The lack of a reliable verbal N400 effect in the LD group prevented a parallel analysis of differential asymmetries for words and sounds in that group.

The results demonstrate physiologic differences between the LD and control group in the processing of related versus unrelated verbal material. However, it is interesting to note that these physiologic differences occurred in the presence of only minimal behavioral differences between groups when subjects were asked to explicitly label stimulus pairs as related or unrelated. This dissociation of behavior and electrophysiology is reminiscent of that observed by Kutas and colleagues in commissurotomy patients [38]. When semantically congruent or incongruent sentence endings were presented to one or the other visual field, right-visual-field (left hemisphere) presentations elicited normal N400 context effects in all five "split-brain" patients tested. N400 context effects after left-visual-field (right hemisphere) presentation were observed in only two of the patients; these two were also able to read aloud words presented to their right hemispheres, and had demonstrated some right-hemisphere syntactic competence. The striking dissociation involved the mute right hemispheres of the other three patients: although congruent and incongruent words presented to these hemispheres did not elicit differential N400s, the patients were able to point to cards labeled 'sense' or 'nonsense' with greater than 70% accuracy. The commissurotomy results thus suggested that nonspecialized cognitive mechanisms could make binary distinctions about semantic relationships, but that N400 activity was dependent on full language competence by a hemisphere. The LD subjects of the current study were not, of course, as language-impaired as the typical right hemisphere of a commissurotomy patient. However, the pattern of results across the two studies suggests that the ERPs recorded in a rather simple semantic task are more sensitive to dysfunction than behavioral judgements would suggest.

The behavior/physiology dissociation raises two interesting possibilities concerning adult LD subjects. First, the presence of ERP differences during semantic processing despite high behavioral accuracy in identifying related and unrelated word pairs suggests that the LD group may have used different physiological mechanisms to accomplish the task of semantic association. However, the small group difference in behavioral performance (a less than 3% accuracy deficit for the LD group), combined with the poor vocabulary scores of the LD group suggests that these alternate physiological mechanisms are less than optimal for supporting verbal semantic skills. One may speculate that a reduced capacity for implicit recognition of semantic links in the verbal domain might underlie previously reported deficits in both vocabulary learning and fast mapping paradigms, in that the ability to form semantic links between labels and attributes is critical to successful performance on these tasks [10,15,24,34,61–63]. Moreover, our results suggest that the difficulties that these individuals experience in learning new vocabulary is not linked to a general semantic deficit spanning both verbal (e.g., lexical labels) and nonverbal domains (e.g., semantic attributes). Instead, the limited nature of the processing differences found implicates difficulties with the verbal domain only. Likewise the ERP data argue against previous suggestions [69] that these children's difficulty may lie in the ability to form associations between the nonverbal and verbal domains. The present ERP data suggest that processing differences within the verbal domain may be sufficient to account for problems in forming semantic associations.

Second, the N400 deficit in high functioning adults suggests that the group differences reflect long-term and probably stable physiologic characteristics, although these individuals have compensated well enough to attend regular college classes. The residual physiological abnormality in the present group parallels previous reports of a high prevalence of atypical neuroanatomical features observed in the adult language or learning disabled population on autopsy [20,32] and in studies that used magnetic resonance imaging [7,11,33,35, 36,42]. Autopsy studies have documented structural anomalies at both the cellular and gross anatomical levels. These include cortical ectopias, focal dysplasias, and anomalous patterns of symmetry in language-related cortex. Imaging studies have revealed both anomalous patterns of cerebral asymmetry and alterations in the number and morphology of cortical gyri. These neuroanatomical features can be found in both the left and right hemispheres and are most commonly documented in the perisylvian regions, including the inferior frontal gyrus, superior temporal, and temporal-parietal regions. Although these neuroanatomic effects reflect alterations of prenatal and perinatal brain development, they persist into adult life. These longstanding anatomical effects may well relate to the persistence of both behavioral deficits and physiological effects in this population. As yet, the functional relationships between these atypical neuroanatomical features and physiological effects of the sort reported here remain to be investigated.

The observed LD deficit in processing conceptual relationships was specific to words, but the results are amenable to more than one account of the source of this deficit. For word pairs, the conceptual or semantic level is the endpoint of processing, so that the absence of a semantic N400 effect may reflect impairments at earlier levels of analysis. Spoken words and environmental sounds differ in their acoustic characteristics, so that it is possible that the dissociation between words and sounds reflects abnormal phonological processing which in turn leads to abnormal semantic processing for spoken words but not nonspeech stimuli. This conclusion is suggested by one report of an abnormal auditory mismatch negativity for speech, but not pure tone stimuli in developmental language disorder [64]. However, another laboratory reports N400 deficits with purely visual stimuli, so that it may also be plausible to hypothesize a semantic deficit which is not contingent on phonological troubles earlier in the processing stream [52,68]. To date, experimental paradigms have focused on either sensory/phonological processes, or on semantic processes; the relationships between these levels will be clearer when both are examined in the same subjects.

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Appendix A. Related word pairs

apple	orange
arm	leg
automobile	car
bacon	egg
bathtub	shower
beach	ocean
beard	mustache
bed	blanket
bee	wasp
belt	buckle
blouse	shirt
bolt	screw
bowl	spoon
bread	toast
broom	mop
bucket	pail
butterfly	moth
camera	film
canoe	paddle
carrot	celery
cavity	tooth
chipmunk	squirrel
cigar	cigarette
city	town
coat	jacket
cobra	snake
colt	calf
comb	brush
couch	sofa
deer	elk
dolphin	whale
dress	skirt
duck	goose
eye	ear
finger	thumb
forest	tree
frog	toad
hamburger	hotdog
hammer	nail
hand	foot
hat	head
heart	lung
hen	rooster
horse	cow
kitchen	sink
kitten	puppy
knife	fork
lemon	lime
letter	stamp
library	book
lion	tiger
lock	key
mitten	glove
needle	thread
nickel	dime
nose	face
onion	garlic
oyster	clam
peach	plum
pedal	bike
pen	pencil
prison	jail
purse	wallet
railroad	train
rake	hoe
rat	mouse
river	stream
rock	stone
saguaro	cactus
salt	pepper
scarf	neck
sheep	lamb
shingle	roof
shoe	sock
shotgun	rifle
snail	slug
stove	oven
sun	moon
table	chair
tarantula	spider
tavern	bar
thorn	rose
tortoise	turtle
vampire	bat
vase	flower
walrus	seal
washcloth	towel
wolf	fox

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