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# Specific language and reading skills in school-aged children and adolescents are associated with prematurity after controlling for IQ

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ABSTRACT

Although studies of long-term outcomes of children born preterm consistently show low intelligence quotient (IQ) and visual-motor impairment, studies of their performance in language and reading have found inconsistent results. In this study, we examined which specific language and reading skills were associated with prematurity independent of the effects of gender, socioeconomic status (SES), and IQ. Participants from two study sites ($N = 100$) included 9–16-year old children born before 36 weeks gestation and weighing less than 2500 grams (preterm group, $n = 65$) compared to children born at 37 weeks gestation or more (full-term group, $n = 35$). Children born preterm had significantly lower scores than full-term controls on Performance IQ, Verbal IQ, receptive and expressive language skills, syntactic comprehension, linguistic processing speed, verbal memory, decoding, and reading comprehension but not on receptive vocabulary. Using MANCOVA, we found that SES, IQ, and prematurity all contributed to the variance in scores on a set of six non-overlapping measures of language and reading. Simple regression analyses found that after controlling for SES and Performance IQ, the degree of prematurity as measured by gestational age group was a significant predictor of linguistic processing speed, $\beta = -.27$, $p < .05$, $R^2 = .07$, verbal memory, $\beta = .31$, $p < .05$, $R^2 = .09$, and reading comprehension, $\beta = .28$, $p < .05$, $R^2 = .08$, but not of receptive vocabulary, syntactic comprehension, or decoding. The language and reading domains where prematurity had a direct effect can be classified as fluid as opposed to crystallized functions and should be monitored in school-aged children and adolescents born preterm.



Approximately one in eight children in the United States is born prematurely (Committee on Understanding Premature Birth and Assuring Healthy Outcomes, Behrman, & Butler, 2007), a worrisome public health statistic because children born preterm have poorer neurodevelopmental outcomes than children born at term (Fletcher et al., 1997; Hack, 2006; Msall & Tremont, 2002; Ornstein, Ohlsson, Edmonds, & Asztalos, 1991; Rose & Feldman, 1996; Rose, Feldman, & Jankowski, 2009; Strang-Karlsson et al., 2010). Among children born before 32 weeks gestation or weighing less than 1500 grams at birth, major disabilities, including cerebral palsy, sensory impairment, intellectual disability, or seizure disorder occur in up to 20% of survivors (Mikkola et al., 2005). Less severe disabilities, including language-based learning disabilities occur in at least 40–50% of survivors (Aylward, 2002; Grunau, Whitfield, & Davis, 2002; Hille et al., 1994). Even children born late preterm, at 32–36 weeks gestation, have poorer school outcomes than full-term peers (Chyi, Lee, Hintz, Gould, & Sutcliffe, 2008). Adverse outcomes have been attributed primarily to a distinctive pattern of injury to the periventricular cerebral white matter and associated neuronal and axonal abnormalities (Back, Riddle, & McClure, 2007; Fletcher, Francis, Thompson, Davidson, & Miner, 1992; Kinney, 2006; Luciana, 2003; Nagy et al., 2003; Soria-Pastor et al., 2008; Vangberg et al., 2006; Volpe, 2009; Yung et al., 2007).

Accounts of language outcomes in children born preterm are highly variable, in contrast to consistent reports of low intelligence quotient (IQ) and impairments in motor skills, visual processing, and visual-motor integration in this population (de Kieviet, Piek, Aarnoudse-Moens, & Oosterlaan, 2009; O'Connor & Fielder, 2007; Rose, Feldman, Jankowski, & Van Rossem, 2005; Rose, Feldman, Jankowski, & Van Rossem, 2008). Some studies find clinically significant language deficits in their preterm samples (Caldu et al., 2006; Foster-Cohen, Friesen, Champion, & Woodward, 2010; Guarini et al., 2009a; Van Lierde, Roeyers, Boerjan, & De Groote, 2009) whereas other studies report no significant language deficits (Kilbride, Thorstad, & Daily, 2004; Menyuk, Liebergott, & Schultz, 1995; Saigal et al., 2006; Stolt et al., 2007). Reading problems have

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been associated with prematurity in several studies (Anderson & Doyle, 2003; Andrews et al., 2010; Hack et al., 1994; O'Callaghan et al., 1996; Saigal, Hoult, Streiner, Stoskopf, & Rosenbaum, 2000) but not all (Frye, Landry, Swank, & Smith, 2009; Hutton, Pharoah, Cooke, & Stevenson, 1997). In those studies with positive results, reading problems have not been well characterized.

Could language and reading difficulties after prematurity be explained primarily on the basis of the low IQ of this population? One possibility is that preterm birth and its complications affect all domains of cognitive and language function equally. An alternative possibility is that preterm birth is associated with domain-specific impairments that are dissociable from general cognitive deficits but difficult to detect because they co-occur with low IQ. Children born preterm score up to 20 points less than children born at term on IQ measures (Aylward, 2002; Bhutta, Cleves, Casey, Cradock, & Anand, 2002; Hack et al., 2002). IQ differences remain even after controlling for gender, socioeconomic status (SES), race, and ethnicity and after excluding children with severe disabilities from the study population (Bhutta et al., 2002). Although controlling for IQ in studies of neurodevelopmental disorders may mask important group characteristics, it is appropriate to do so when the theoretical question of interest is whether there are direct effects of the independent variable (in this case, prematurity) on the outcome (in this case, language and reading skills) (Dennis et al., 2009). Nadeau and colleagues found that the effect of prematurity on behavior problems disappeared when intelligence and neuromotor function were introduced into analyses as mediators (Nadeau, Boivin, Tessier, Lefebvre, & Robaey, 2001). Would controlling for IQ also eliminate differences between children born preterm and full-term in domains of language and reading?

In support of the possibility that all domains of function are equally affected by preterm birth, Aram and colleagues observed that language dysfunction in children born preterm is primarily related to IQ (Aram, Hack, Hawkins, Weissman, & Borawski-Clark, 1991). They found that Specific Language Impairment (SLI), defined as language abilities significantly below what would be expected on the basis of IQ, was no more prevalent among children born preterm than among the general population. Similarly, in the domain of reading, poor single word reading (also referred to as decoding skills) has been explained solely on the basis of poor cognitive and language abilities in children born preterm (Frye et al., 2009). In contrast, other studies find that language and reading difficulties in children born preterm are not attributable exclusively to cognitive abilities, suggesting that features or complications of prematurity further compromise language function (Briscoe, Gathercole, & Marlow, 1998; Briscoe, Gathercole, & Marlow, 2001; Guarini et al., 2009b; Landry, Smith, & Swank, 2002; Roze et al., 2009; Taylor, Klein, Minich, & Hack, 2000). Moreover, factors such as age (Botting, Powls, Cooke, & Marlow, 1998; Ment et al., 2003; O'Brien et al., 2004), gender (Hintz, Kendrick, Vohr, Poole, & Higgins, 2006; Sansavini et al., 2006), and SES (Gross, Mettelman, Dye, & Slagle, 2001; Hutton et al., 1997; Richards & Wadsworth, 2004; Sansavini et al., 2007; Tideman, 2000) may moderate or confound relationships among prematurity, intelligence, and language outcomes. For example, two risk factors associated with language, speech, and reading problems in the general population—male gender and low SES—are also risk factors for both prematurity and adverse outcomes of prematurity (Feldman & Loe, 2007).

A few studies of children born preterm have evaluated specific subdomains within the broad domains of language and reading. An Italian study by Sansavini and colleagues found that as preschoolers, children born preterm without obvious neural injuries had persistent and mildly poorer grammatical skills and verbal working memory than children born at term (Sansavini et al., 2006). Another study of children without major neurological sequelae reported that prematurity was associated with lower scores on a picture vocabulary test (Caravale, Tozzi, Albino, & Vicari, 2005). Children born preterm have also been found to show poorer and slower naming abilities at 9 years of age (Saavalainen et al., 2006). Unfortunately, these analyses did not consider the contribution of IQ differences between groups on the language outcomes. Aylward (2002) summarized a series of studies, reporting that vocabulary and receptive language were generally intact but syntactic skills were deficient after prematurity.

The overall goal of this study was to characterize component skills of language and reading in children and adolescents 9–16 years of age who were born preterm in comparison to full-term peers. The first aim was to compare a group of children born preterm to a group of full-term controls matched for age, gender, and socioeconomic status (SES). Because of the overall high rates of disabilities among children born preterm, we hypothesized that within the domains of language and reading, children born preterm would perform at lower levels than children born at term. Moreover, because other studies document that in general the most immature and smallest infants have the most severe neurodevelopmental outcomes (Committee on Understanding Premature Birth and Assuring Healthy Outcomes et al., 2007), we hypothesized that children born at an extremely low gestational age would perform at lower levels than preterm children born at later gestational ages.

The second aim of the study was to determine whether differences between children born preterm and controls could be explained solely on the basis of IQ differences between groups or whether prematurity was an independent risk factor for language and reading problems after controlling for the effects of IQ. We hypothesized that prematurity would be an independent risk factor because IQ does not adequately explain poor academic function in these children. We performed separate analyses controlling for Performance IQ and Verbal IQ because the potential overlap of skills in language or reading with Verbal IQ might lead to different results in the two analyses.

The third aim of the study was to determine which subdomains of language and reading would be affected by prematurity after controlling for IQ as well as SES. We formulated hypotheses based on the theoretical distinction between "fluid" and "crystallized" functions within the cognitive domain (Pennington, 2008) that has proven useful in differentiating among cognitive abilities, and in particular, in explaining deficient versus preserved skills after brain injury. Fluid functions, also called fluid reasoning, refer to the abilities required to solve novel problems. In contrast, crystallized functions refer to the abilities used to apply accumulated, primarily verbal, knowledge. Brain injury has a greater negative impact on fluid than crystallized functions (Cattell, 1963). We hypothesized that prematurity would have more adverse consequence for fluid functions than for crystallized functions because preterm birth is associated with white matter injury.

For this third aim, we classified the specific abilities assessed in this study based on an interpretation of the distinction between fluid and crystallized function that Taylor and colleagues used specifically for children born preterm: processing efficiency reflects fluid reasoning and accumulation of verbal-semantic knowledge crystallized abilities (Taylor et al., 2000). We classified reaction time to interpret syntactic constructions (linguistic processing speed) and verbal memory as fluid functions because these measures assessed efficiency in processing novel stimuli. We classified receptive vocabulary, assessed on an untimed standardized test, as a crystallized function because it measured accumulated verbal-semantic knowledge. We were uncertain about how to classify accuracy in syntactic comprehension, single word reading or decoding skills, or reading comprehension in middle childhood and adolescence. Though these skills are likely reflective of fluid abilities at young ages when children are first acquiring them, they may become sufficiently practiced to be conceptualized as crystallized

**Table 1**
Demographics of all participants ($N = 100$) and group with complete scores ($n = 85$).

| Characteristics | All participants | | | Group with complete scores | | |
|---|---|---|---|---|---|---|
| | Preterm ($n = 65$) | Control ($n = 35$) | $X^2$ or $t$ | Preterm ($n = 54$) | Control ($n = 31$) | $X^2$ or $t$ |
| Boys – $n$ (%) | 35 (53.8) | 16 (45.7) | 0.60 | 28 (51.9) | 15 (48.4) | 0.10 |
| Low maternal education – $n$ (%) | 21 (32.3) | 15 (42.9) | 1.10 | 16 (29.6) | 12 (38.7) | 0.74 |
| Mean age in years (SD, Range) | 12.2 (1.8, 6.8) | 12.6 (2.1, 7.1) | 1.01 | 11.9 (1.7, 6.8) | 12.6 (2.1, 7.1) | 1.59 |
| Mean birth weight in grams (SD, Range) | 1215 (465, 2128) | 3425 (499, 1984) | 22.10*** | 1241 (494, 2128) | 3375 (491, 1899) | 19.22*** |
| Mean gestational age in weeks (SD, Range) | 28.8 (2.7, 11.5) | 39.5 (1.2, 5.0) | 27.24*** | 28.9 (2.7, 11.5) | 39.4 (1.1, 5.0) | 25.01*** |

SD = standard deviation.
Range = difference between the highest and lowest value.
*** $p < .001$.

abilities by the time children reach middle childhood. We reasoned that if we were to find the expected associations of prematurity with vocabulary, linguistic processing speed, and verbal memory, then the results themselves might suggest which language-based skills remain indicative of fluid functions at school age and beyond.

## 1. Methods

### 1.1. Participants

The study participants were part of a two-site study conducted in Pittsburgh, PA and Palo Alto, CA, who were participating in a study of language, cognitive, and executive function skills in children born prematurely. This study was approved by the Children's Hospital of Pittsburgh/University of Pittsburgh, and Stanford University institutional review boards. A parent or legal guardian provided informed consent, and children provided assent. Children were compensated for participation.

Inclusion criteria for participants included age 9–16 years and ability to cooperate with testing. Study subjects had a history of preterm birth (<36 weeks gestation) and birth weight <2500 grams. Controls were born full-term (≥37 weeks). Exclusion criteria for all participants included active seizure disorder and/or anticonvulsant medication use; history of infection, revisions, or complications of ventriculo-peritoneal shunt for treatment of hydrocephalus; presence of neurological lesions, such as congenital malformation, meningitis, or encephalitis; estimated receptive vocabulary score <70; sensorineural hearing loss; and non-English speaker. For controls, additional exclusion criteria included history of preterm birth; presence of an identified language, learning, or attention disorder; other Axis I psychiatric disorder; and retention in grade after age 7 years. Controls had stricter criteria because these data were also used in an MRI study investigating group differences, for which potential neurologic abnormalities associated with neurobehavioral disorders needed to be ruled out. Preterm subjects were recruited by letters and flyers posted in local early intervention newsletters distributed in Pittsburgh and surrounding areas. Preterm subjects in Palo Alto were recruited through letters from attending physicians sent to families of children who were evaluated at the High-Risk Infant Follow-up Services at Lucile Packard Children's Hospital. Control children were recruited by local ads, postings in school newsletters, and word of mouth at both sites. Controls were group-matched to children born preterm for age, gender, race, and maternal education as a measure of SES. Demographic data for 100 children (65 preterms and 35 controls), who went through both testing sessions are presented in Table 1. Maternal education was used as the index for SES. Low maternal education was defined as less than a college degree, and high maternal education was defined as at least a completed college degree. In the total sample, the preterm and full-term groups did not differ significantly in age, gender, and SES. In terms of ethnicity, there were more Hispanics versus Non-Hispanics in the control group than the preterm group. By study design, there was a significant difference in gestational age, preterm = 28.8 weeks, control = 39.5 weeks, $t = 27.24$, $p < .001$, and birth weight, preterm = 1215 grams, control = 3425 grams, $t = 22.10$, $p < .001$.

Medical complications at birth in the preterm group were as follows: 16 (24.6% of the preterm group) had abnormal findings on head ultrasounds or MRIs (at least grade 2 intraventricular hemorrhage, echodensities, or cystic lesions), 8 (12.3%) had mildly abnormal findings (defined as either grade 1 hemorrhage or choroid plexus cyst); 23 (35.3%) had respiratory distress syndrome and 9 (13.8%) developed chronic lung disease; and 5 (7.6%) were small for gestational age (defined as lying at or below the 3rd percentile in birth weight for gestational age).

Out of the total sample, 85 (54 preterms and 31 controls) had complete data for all behavioral measures (Table 1). Missing scores were due to errors in test administration and a change in protocol at the beginning of the study.

*IQ-matched subsamples.* From the complete-score sample, two subsamples that were carefully matched for SES and IQ were created, Performance IQ (PIQ)-matched ($n = 58$) and Verbal IQ (VIQ)-matched ($n = 54$). The following criteria were used to maximize the subsample size while retaining a close IQ match:

1. The relevant IQ scores of the preterm and full-term pair were within five points.
2. The pair had the same maternal education level, either both low or both high.
3. If there were more than one preterm who matched to a full-term, the preterm with the closest IQ score was selected.

It was not a priority to match gender because gender did not have a significant effect on behavioral measures (see Section 2). However, we were able to match gender for all but five pairs in the PIQ-matched sample and five pairs in the VIQ-matched sample.

### 1.2. Behavioral measures

Subjects underwent two testing sessions to assess language skills, cognitive abilities, and executive function. Assessments and standard scores were based on birth date. Measures included in this study are as follows, organized by the function being assessed:

*General cognitive abilities*: The Wechsler Abbreviated Scale of Intelligence (WASI) is a widely used, nationally standardized test of general intellectual ability that measures both verbal and nonverbal cognitive ability (Horn, 1995; Kaufman, 1994; Wechsler, 1999; Woodcock, 1990). Performance IQ is composed of Block Design and Matrix Reasoning subtests and assesses nonverbal abilities. Verbal IQ is composed of Vocabulary and Similarities subtests and assesses verbal intelligence.

*Receptive and expressive language skills*: The Comprehensive Evaluation of Language Fundamentals–Fourth Edition (CELF-4) is a norm-referenced test for the identification, diagnosis, and follow-up evaluation of language and communication disorders in students 5–21 years old (Semel, Wiig, & Secord, 2003). The Receptive Language Index (RLI) and Expressive Language Index (ELI) from the CELF-4 were generated. The RLI is a measure of listening and auditory comprehension. For ages 9–12 years, the RLI is composed of Word Classes 2-Receptive and Concepts and Following Directions; for ages 13–21 years, the RLI is composed of Word Classes 2-Receptive, Semantic Relationships, and Understanding Spoken Paragraphs. For all age groups, the ELI is a measure of language production and is composed of Word Classes 2-Expressive, Formulated Sentences, and Recalling Sentences.

*Receptive vocabulary*: Peabody Picture Vocabulary Test–Third Edition (PPVT-III) is a widely used test of receptive vocabulary that generates a standard score (Dunn & Dunn, 1997). Each item consists of four black-and-white drawings on a page. Subjects are asked to identify which of the four illustrations best represents the stimulus word presented orally by the examiner.

*Syntactic comprehension*: Two tests of on-line sentence comprehension were combined to generate a score for syntactic comprehension. First, the Test for Reception of Grammar–Version Two (TROG-2) is a computerized measure that assesses syntactic comprehension by presenting sentences in the auditory mode and using a four picture multiple choice format with lexical and grammatical foils (Bishop, 2003). We chose this test because it is a pure measure of syntax, and it generates both an error score and a processing speed. The vocabulary is simple and familiar to school-aged children. Subjects can press a button to hear the sentence as many times as necessary. The test, consisting of 80 items, organized into 20 four-sentence blocks of increasing syntactic difficulty, is designed to tap grammatical skills of school-aged children and adolescents. The error score is the total number of errors out of 80 items. Second, we also created sentence-picture verification tasks that consist of the presentation of the same sentences verbally followed by the presentation of a single picture. Subjects decide whether the picture matches the sentence by pressing a yes or no button. We used both measures to increase the variance in syntactic comprehension. Because syntactic comprehension errors correlated with age, an age-adjusted $z$-score was calculated for each subject.

*Linguistic processing speed*: The TROG-2 results were used for this measure. The reaction time for each item is the time it took for subjects to respond to the sentence by selecting the matching picture. The mean reaction time was calculated from correct trials only. We also excluded trials in which the subject repeated the sentence presentation in order to eliminate from analysis distractions and re-checked responses of very high-functioning children.

*Verbal memory*: The Language Memory Index (LMI) from the CELF-4 provides a measure of the ability to apply working memory to linguistic content and structure. It is composed of the following subtests: Formulated Sentences, Recalling Sentences, as well as Concepts and Following Directions for ages 9–12 and Semantic Relationships for ages 13–21.

**Table 2**
Mean scores (standard deviation) in subdomains of intelligence, language, and reading for four groups: extremely low gestational age (ELGA, ≤27 weeks) preterm, very low/low GA (VLGA, ≥28 weeks) preterm, all preterm (<36 weeks), and full-term groups (≥37 weeks).

| Domain | Assessment measure | *n* | ELGA | VLGA | All preterm | Control | *F* |
|---|---|---|---|---|---|---|---|
| Nonverbal abilities | WASI, Performance IQ, SS | 100 | 95.7 (18.3) | 102.9 (14.4) | 100.1 (16.3) | 112.0 (12.5) | 9.14*** |
| Verbal intelligence | WASI, Verbal IQ, SS | 100 | 101.3 (16.7) | 104.6 (15.3) | 103.3 (15.8) | 114.3 (14.1) | 6.35** |
| Receptive language skills | CELF-4, Receptive Language Index, SS | 93 | 99.7 (16.9) | 102.9 (15.9) | 101.6 (16.2) | 110.7 (12.6) | 4.21* |
| Expressive language skills | CELF-4, Expressive Language Index, SS | 100 | 99.2 (15.1) | 103.2 (15.9) | 101.6 (15.6) | 110.2 (12.1) | 4.60* |
| Receptive vocabulary | PPVT-III, SS | 100 | 105.2 (15.4) | 110.8 (15.2) | 108.6 (15.4) | 113.0 (12.9) | 2.22 |
| Syntactic comprehension | Sentence comprehension, error z score | 99 | 1.31 (2.1) | 0.18 (1.4) | 0.63 (1.8) | 0.02 (1.0) | 6.10** |
| Linguistic processing speed | TROG-R Reaction time, milliseconds | 92 | 3107 (487) | 2661 (604) | 2827 (600) | 2511 (493) | 8.34*** |
| Verbal memory | CELF-4, Language Memory Index, SS | 93 | 97.7 (16.8) | 101.7 (15.8) | 100.1 (16.2) | 110.6 (10.5) | 6.23** |
| Decoding | WJ-III Basic Reading Skills Cluster, SS | 100 | 102.2 (14.4) | 103.7 (11.3) | 103.1 (12.5) | 110.1 (9.9) | 4.24* |
| Reading comprehension | WJ-III Passage Comprehension, SS | 100 | 98.2 (11.4) | 101.5 (13.7) | 100.1 (12.8) | 109.4 (12.9) | 6.41** |

WASI = Wechsler Abbreviated Scale of Intelligence; CELF-4 = Clinical Evaluation of Language Fundamentals – 4th Edition; PPVT-III = Peabody Picture Vocabulary Test - 3rd Edition; TROG-R = Test for Reception of Grammar–Revised; WJ-III = Woodcock–Johnson Tests of Achievement – 3rd Edition.
SS = standard score.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

*Decoding*: The Woodcock-Johnson III Tests of Achievement (WJ-III) assesses reading abilities (Woodcock, McGrew, & Mather, 2001). The Basic Reading Skills Cluster assesses decoding skills, the ability to translate written letters into speech sounds and recognize written words, and is a composite score of two subtests: Letter-Word Identification (single word reading) and Word Attack (pseudoword reading).

*Reading comprehension:* The WJ-III Passage Comprehension subtest assesses reading comprehension skills.

### 1.3. Statistical analysis

Alpha level was set at $p < .05$ for statistical significance but trends approaching statistical significance were noted. Chi-square tests (for categorical variables) and independent *t*-tests or analyses of variance (ANOVAs) (for continuous variables) were used to evaluate between-group differences.

Multivariate analyses of covariance (MANCOVAs) were performed on the group with complete scores to examine relationships among the language and reading outcome set, fixed factors, and covariates. In addition to the *F* statistic, we calculated the *partial* $\eta^2$ (eta squared) for each fixed factor and covariate. *Partial* $\eta^2$ is the proportion of variance a variable explains that is not explained by other variables in the model.

To explore the direct effects of prematurity on individual subdomains of language and reading function after controlling for IQ and SES, we performed linear regressions on each of the six language and reading measures that comprised the outcome set in the MANCOVA. Gestational age (GA) group was used as the predictor in the regression models to index both prematurity and the degree of prematurity. We chose gestational age over birth weight because it is a physiologic index of the degree of prematurity uncomplicated by growth retardation. However, birth weight and gestational age were highly correlated in this sample, $r = .95$, $p < .001$. We chose to group by GA rather than use it as a continuous variable because we did not anticipate a relation between GA and outcomes within the full-term participants. We used three GA categories in order to create near-equivalent sized groups: [1] extremely low GA (ELGA) defined as GA ≤ 27 weeks, [2] very low/low GA (VLGA) defined as GA 28–36 weeks, and [3] full-term. In the multiple hierarchical regression analyses, SES was entered as a predictor first, IQ second, and GA group third.

## 2. Results

Children born preterm scored more poorly in all domains of cognitive, language, and reading function than full-term controls (Aim 1). As hypothesized, the ELGA group scored more poorly than the VLGA group. Table 2 shows the summary of group mean scores and standard deviations for each measure. Significant group differences were found in all domains with the exception of receptive vocabulary: Performance IQ, $F(2,97) = 9.14$, $p < .001$; Verbal IQ, $F(2,97) = 6.35$, $p < .01$; receptive language skills, $F(2,90) = 4.21$, $p < .05$; expressive language skills, $F(2,97) = 4.60$, $p < .05$; syntactic comprehension (in error z score), $F(2,96) = 6.10$, $p < .01$; linguistic processing speed (in milliseconds), $F(2,89) = 8.34$, $p < .001$; verbal memory, $F(2,90) = 6.23$, $p < .01$; decoding, $F(2,97) = 4.24$, $p < .05$; and reading comprehension, $F(2,97) = 6.41$, $p < .01$. Post hoc analyses found that the ELGA group was significantly different from the control group in all domains. The VLGA group was significantly different from the control group only in Performance IQ, Verbal IQ, verbal memory, and reading comprehension. The ELGA group was significantly different from the VLGA group only in syntactic comprehension and linguistic processing speed.

To assess whether prematurity independently contributed to language and reading skills, we conducted two MANCOVA analyses (Aim 2). We chose this analytic strategy to reduce the possibility of error and increase the likelihood of detecting an effect. In both analyses, gender, SES (high versus low maternal education), and prematurity (as a binary variable) were fixed factors. In the first analysis, we covaried for Performance IQ and in the second for Verbal IQ. A set of six non-overlapping measures was evaluated in these analyses. We chose five of the six measures—linguistic processing speed, verbal memory, syntactic comprehension, decoding, and reading comprehension—because we had found significant group differences in these scores on the univariate analyses (Table 2). Though group differences did not achieve statistical significance for receptive vocabulary, we included this measure in the model as well because semantics is a key subdomain within the domain of language. We did not include the RLI and ELI of the CELF-4 in the models because the subtests that contribute to those scores overlap with the subtests that generate the LMI, the measure of verbal memory.

As shown in Table 3, Performance IQ contributed to the variance in language and reading skills, $F(6, 71) = 10.39$, $p < .001$, *partial* $\eta^2 = .47$. As hypothesized, after controlling for Performance IQ, prematurity contributed to the model $F(6, 71) = 3.38$, $p < .01$, *partial*

**Table 3**
Multiple analyses of covariance (MANCOVA) for the set of six non-overlapping measures of language and reading—linguistic processing speed, verbal memory, receptive vocabulary, syntactic comprehension, decoding, and reading comprehension.

| | | *F* | Partial $\eta^2$ |
|---|---|---|---|
| Covariate: | Performance IQ | 10.39*** | .47 |
| Factors: | Gender | 1.76 | .13 |
| | SES | 3.45** | .23 |
| | Prematurity | 3.38** | .22 |
| Covariate: | Verbal IQ | 17.32*** | .59 |
| Factors: | Gender | 1.67 | .12 |
| | SES | 2.49* | .17 |
| | Prematurity | 2.72* | .19 |

SES = socioeconomic status, indexed by maternal education level.
Prematurity = a binary variable.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

**Table 4**
Simple regressions for an ordinal variable of gestational age (GA group) predicting to language and reading abilities in preterm and full-term pairs matched for socioeconomic status (SES) and performance or verbal IQ.

| | $R^2$ | B (SE) | β |
|---|---|---|---|
| (a) Matched for SES and Performance IQ ($n$ = 58). | | | |
| Linguistic processing speed | .07 | −202.01 (96.34) | −.27* |
| Verbal memory | .09 | 5.48 (2.29) | .31* |
| Receptive vocabulary | .01 | 2.14 (2.70) | .11 |
| Syntactic comprehension | .02 | −0.25 (0.21) | −.15 |
| Decoding | .01 | 1.33 (1.83) | .10 |
| Reading Comprehension | .08 | 4.97 (2.32) | .28* |
| (b) Matched for SES and Verbal IQ ($n$ = 54). | | | |
| Linguistic processing speed | .09 | −221.50 (99.45) | −.30* |
| Verbal memory | .05 | 4.33 (2.54) | .23″ |
| Receptive vocabulary | .00 | −0.52 (2.64) | −.03 |
| Syntactic comprehension | .01 | −0.21 (0.28) | −.10 |
| Decoding | .00 | −0.17 (1.99) | −.01 |
| Reading comprehension | .05 | 3.83 (2.35) | .22 |

SE = standard error.
* $p < .05$.
″ $p \leq .094$.

$\eta^2 = .22$. There was also a significant effect of SES, $F(6, 66) = 3.45$, $p < .01$, *partial* $\eta^2 = .23$. The result of the MANCOVA with Verbal IQ as the covariate was very similar. Verbal IQ contributed to the variance in language and reading skills, $F(6, 71) = 17.32$, $p < .001$, *partial* $\eta^2 = .59$. In addition, after controlling for Verbal IQ, prematurity contributed to the model, $F(6, 71) = 2.72$, $p < .05$, *partial* $\eta^2 = .19$. There was also a significant effect of SES, $F(6, 71) = 2.49$, $p < .05$, *partial* $\eta^2 = .17$. Gender did not have a significant effect in either model.

To evaluate the direct impact of the degree of prematurity on each language domain separately (Aim 3), we carefully matched children born preterm to children born full-term on the basis of SES and either Performance or Verbal IQ. We then used a simple regression analysis to evaluate the contribution of GA group. Table 4 presents the results of these analyses on the PIQ-matched and VIQ-matched subsamples. After matching on Performance IQ and SES, GA group was a significant predictor of linguistic processing speed, $\beta = -.27$, $p < .05$, $R^2 = .07$, verbal memory, $\beta = .31$, $p < .05$, $R^2 = .09$, and reading comprehension, $\beta = .28$, $p < .05$, $R^2 = .08$. Results were similar after matching on Verbal IQ and SES; GA group was a significant predictor of linguistic processing speed, $\beta = -.30$, $p < .05$, $R^2 = .09$, and approached significance as a predictor of verbal memory, $\beta = .23$, $p = .094$, $R^2 = .05$.

## 3. Discussion

We found that, as hypothesized, children born preterm had poorer language and reading abilities than full-term controls (Aim 1). The ELGA group had lower scores than the VLGA group on all measures, and the differences reached statistical significance in two subdomains. Language and reading skills were associated with prematurity independent of the effects of gender, SES, and IQ (Aim 2). Of the six non-overlapping subdomains we evaluated—linguistic processing speed, verbal memory, receptive vocabulary, syntactic comprehension, decoding, and reading comprehension—the degree of prematurity as indexed by GA group was a direct predictor of linguistic processing speed, verbal memory, and reading comprehension (Aim 3). GA group was not a direct predictor of receptive vocabulary, syntactic comprehension, or decoding. These findings support the hypothesis that prematurity has a greater impact on fluid than crystallized functions. Not surprisingly, the amount of variance explained by prematurity was small because we controlled for IQ in these analyses. Since low IQ is a consequence of prematurity, controlling for it reduces the impact of prematurity, as the independent variable, on language function, as the dependent variable (Dennis et al., 2009).

In the discussion that follows, we focus on the impact of prematurity on the specific subdomains of language and reading we studied. We first discuss linguistic processing speed and verbal memory, classified as fluid functions. We then discuss receptive vocabulary, classified as a crystallized function. Finally, we discuss syntactic comprehension, decoding, and reading comprehension, subdomains which we *a priori* did not classify as fluid or crystallized functions.

Prematurity had the highest impact on linguistic processing speed, which we had classified as a fluid function. As far as we are aware, speed of linguistic processing for syntax has not previously been assessed in children born preterm. The results were similar to the finding that 9-year-old children born preterm were slower in a naming task than controls (Saavalainen et al., 2006). Studies of processing speed in other domains have yielded similar results. Compared to full-terms, children born preterm were found to be slower in a test of perceptual apprehension where they had to correctly identify and discriminate between incoming stimuli (Rose & Feldman, 1996). They were slower in both the intake and processing of information. Later studies by Rose and colleagues reported a cascade of effects resulting from prematurity, in which infant processing speed influenced memory and representational competence, which in turn influenced mental development at age 2–3 years (Rose et al., 2005, 2008). Slower processing speed seems to persist into adulthood (Strang-Karlsson et al., 2010). These studies did not specifically control for the effect of IQ on speed of processing. In the domain of reading, an Italian study found that although 8-year-old children born preterm were not significantly different from controls in general cognitive development, they were slower in word, non-word, and story reading (Guarini et al., 2009b).

The results of this study support the hypothesis that when controlling for Performance IQ, prematurity has a direct impact on verbal memory, which we also had classified as a fluid function. However, when controlling for Verbal IQ, prematurity no longer had a significant direct impact on verbal memory. We suspect that Verbal IQ and verbal memory assess highly overlapping verbal abilities, whereas Performance IQ and verbal memory do not. Accordingly, Verbal IQ absorbs sufficient variance in verbal memory that it reduces the impact of prematurity on verbal memory (Dennis et al., 2009). Indeed, controlling for Verbal IQ reduced the impact of prematurity on all of the measures compared to the results controlling for Performance IQ.

The effect of prematurity on verbal memory after controlling for Performance IQ is consistent with those of several previous studies. Roze and colleagues found that verbal memory was normal in only 50% of children born preterm even after correcting for IQ, whereas poorer visual perception and visuomotor integration were related to lower intellectual level (Roze et al., 2009). In a very low birth weight sample of children, acquisition rates of verbal material were lower than that of controls even after covarying for vocabulary or excluding subjects with IQs < 80 or neurosensory deficits (Taylor et al., 2000). Similarly, Briscoe and colleagues showed that preschool-age children born preterm and at risk for language impairment had deficits in phonological short-term memory (Briscoe et al., 1998). These memory deficits were not attributable to general deficits in intellectual abilities. Moreover, even at age 24 months, the at-risk preterm group had not differed from the no-risk group on general nonverbal abilities (as indexed by the Performance scales of the Griffiths Mental Development Scales), although they had been impaired on language (as indexed by the Hearing and Speech subscale). Language impairment studies in full-term children have suggested that the phonological component of short-term memory is important for multiple domains of language, including vocabulary acquisition (Gathercole & Baddeley, 1993), speech production (Adams & Gathercole, 1996; Blake, Austin, Cannon, Lisus, & Vaughan, 1994), and spoken language comprehension (Crain, Shankweiler, Macaruso, & Bar-Shalom, 1990; Gathercole, Willis, & Baddeley, 1991). Whether the degree of problems in verbal memory is a cause, outcome, or co-traveler with early language delays requires further study.

The results for receptive vocabulary are also consistent with the hypothesis that prematurity has less of an impact on accumulation of verbal-semantic knowledge (crystallized functions) than processing efficiency (fluid functions). We found that receptive vocabulary was not significantly different between children born preterm and controls either before or after controlling for IQ. Our finding is different from that in a study of 5-year-old children born less than 33 weeks, who had receptive vocabulary deficits that could not be ascribed to general cognitive impairment (Briscoe et al., 2001). The previous study, however, did not control for SES. Another possible reason for the discrepancy between our results and those of Briscoe and colleagues is the difference in age. Other studies reported that children born preterm have poorer lexical development at age 6 years (Guarini et al., 2009a) and age 9 years but no longer at age 16 years (Saavalainen et al., 2006). In younger children, tests of receptive vocabulary may assess fluid abilities that evolve to crystallized knowledge over time.

We had no original hypothesis about whether syntactic comprehension is a fluid or crystallized function in this age group. We found that it was not significantly different between children born preterm and controls after controlling for IQ. Our finding suggests that syntactic comprehension functioned like accumulated verbal-semantic knowledge rather than processing efficiency in children 9–16 years of age. A Dutch study of an extremely low birth weight cohort similarly found that comprehension skills even at age 3 years correlated only with general mental functioning (Van Lierde et al., 2009). In addition, in an Italian cohort at age 8 years, grammar comprehension was not significantly different between children born preterm and controls (Guarini et al., 2009b). These findings together suggest that in the subdomain of syntactic comprehension, children born preterm may be resilient even through adolescence. However, we recognize that if tests of syntactic comprehension become extremely difficult, they may require engagement of rapid processing speed, verbal memory, and other skills classified as processing efficiency, and they then may demonstrate differences between preterm and full-term groups.

It was *a priori* unclear whether reading skills should be considered a crystallized function or a fluid function at the ages of these participants. Our results showed that decoding and reading comprehension were significantly different between children born preterm and controls, but we found differing results in the associations of decoding and reading comprehension with GA group and IQ. Prematurity had no direct impact on decoding, but did have a direct impact on reading comprehension after controlling for Performance IQ. Previous studies also report variable results in reading skills. In studies of children with birth weight less than 1000 grams at age 8 and 9 years, group differences in decoding were no longer statistically significant after controlling for IQ (Anderson & Doyle, 2003; Grunau et al., 2002). However, in other studies the same groups were found to be three to five times more likely than controls to have a problem in broad reading (which includes reading comprehension), mathematics, spelling or writing, independent of IQ scores (O'Callaghan et al., 1996; Ornstein et al., 1991; Saigal et al., 2000). The gap in reading comprehension skills between children born preterm and their full-term peers may become more pronounced as they get older and require higher-order reading functions to master complex and abstract reading tasks. Moreover, many children born preterm display non-verbal learning disabilities that are characterized by poorer nonverbal abilities than verbal cognitive skills. In terms of reading, non-verbal learning disabilities are characterized by poorer verbal abstracting and reading comprehension than decoding (Aylward, 2002; Fletcher et al., 1992).

### 3.1. Limitations

The preterm sample in this study had a wide gestational age range. Inclusion of children of low gestational age (GA of 32–36 weeks) with extremely low (GA $\leq$ 28 weeks) and very low gestational age (GA 28–31 weeks) may have reduced the magnitude of the differences between preterm and full-term groups. The evaluation age range was also wide, which may obscure differences related to age in the preterm group. However correlations of standard scores and age were not significant in this sample.

The full-term control sample is small and did not include children with neuropsychiatric or learning problems. Though this bias may increase the degree of differences between groups, the amount of difference was comparable to that seen in other studies (Bhutta et al., 2002).

Another limitation is that we used a dichotomous classification of maternal education level as a measure of SES that may mask other SES differences. Overall, we had a relatively high SES sample, a probable explanation for the high standard scores in both groups. However, the difference between the preterm and full-term groups is comparable to other studies (Bhutta et al., 2002).

### 3.2. Possible neural bases of linguistic processing speed, verbal memory, and reading comprehension

We suspect that the impairments associated with prematurity over and above the impact of IQ in this study relate to specific white matter injuries associated with prematurity. White matter injury accounts for the majority of neuropathologic lesions in children born preterm and persists into school age and beyond (Kinney, 2006; Nagy et al., 2003; Vangberg et al., 2006; Yung et al., 2007). It represents a spectrum of lesions ranging from the focal cystic necrotic lesions of periventricular leukomalacia (PVL), which is declining in incidence, to the noncystic, diffuse myelination disturbances, which represent the majority of cases (Back et al., 2007). White matter injury has been related to a combination of factors, including the immaturity of the vasculature in developing white matter and the particular vulnerability of oligodendroglial precursor cells to infection and hypoxic-ischemic injury between 24 and 32 weeks gestation (Back et al., 2007; Volpe, 2001).

Research studies that have correlated behavioral outcomes with neural imaging techniques suggest that inefficient information processing is a consequence of early, diffuse white matter damage, especially in tracts that connect multiple cortical and subcortical regions (Luciana, 2003; Soria-Pastor et al., 2008). To date, only a few studies have investigated the association of white matter injury and specific language-related abilities in preterm samples. Foster-Cohen investigated language skills in a regionally representative cohort of 110 preterm children and 113 full term controls and found that the severity of neonatal white matter injury on near-term magnetic resonance imaging contributed to the variance in scores at age 4 years (Foster-Cohen et al., 2010). A study of 44 adolescents born preterm showed that low scores on a measure of processing speed correlated with reduction in white matter concentration in the centrum semiovale and posterior periventricular regions (Soria-Pastor et al., 2008). A study of 25 adolescents born preterm found that corpus callosum size significantly correlated with memory performance (Caldu et al., 2006). Risk factors for poor verbal memory are periventricular hemorrhagic infarction and post-hemorrhagic ventricular dilatation (Roze et al., 2009). Memory has also been found to be more sensitive to the effects of intraventricular hemorrhage (IVH) and hydrocephalus than other neuropsychological measures in children born preterm (Fletcher et al., 1997). Finally, a study of

28 school-aged children using diffusion tensor imaging found that microstructural properties of left and right temporoparietal regions of white matter, previously associated with reading performance of children born full-term, were related to reading comprehension in the preterm group (Andrews et al., 2010). This study also reported that microstructure of the mid-body of the corpus callosum correlated with decoding skills. Clearly more research is needed to determine the neural bases of preserved and impaired language and reading function in children born preterm. Of particular clinical importance is the extent to which the developing brain can recover from injury to specific white matter tracts.

### 3.3. Implications and future directions

Children born preterm, even those born late preterm, are at high risk for academic problems. In fact, in one cohort of 9-year-old children born preterm, 81% were in mainstream classrooms without any special education services, but 32% of those students were functioning more than a grade below their placement (Hille et al., 1994). In this study, we found that even when children born preterm were matched with their full-term peers on IQ and SES level, they still showed deficits in areas of language processing efficiency, such as linguistic processing speed and verbal memory, as well as more complex, higher-level skills, such as reading comprehension. Therefore, comprehensive evaluations of school-aged children and adolescents born preterm who are struggling or failing in school should include tests of processing abilities, such as processing speed and memory. More limited evaluations, restricted to accumulated verbal-semantic knowledge, such as vocabulary and decoding, may not adequately reflect the educational needs of the population. Poorer verbal memory and linguistic processing speed may mean that children born preterm require more repetition to consolidate newly-presented information in long-term memory or that they need organization strategies and cuing during the learning process (Taylor et al., 2000).

In the future, we plan to investigate how white matter injury relates to specific subdomains of language and processing abilities in children born preterm. The subdomains of interest in this study, such as linguistic processing speed, verbal memory, reading comprehension, and other measures will be explored in depth with appropriate neuroimaging methods. Studying the population of children born preterm with brain injuries may also help illuminate the categories of fluid and crystallized functions and how they evolve over healthy development. A sequential chain of effects that starts with preterm birth may lead to specific deficiencies in cognitive, language, and reading skills, as well as to problems in neuromotor function and behavior (Aylward, 2002; Nadeau et al., 2001; Rose et al., 2008). Future studies must investigate whether medical and educational interventions can improve function and disrupt this sequence.

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