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Predicting text reading skills at age 8 years in children born preterm and at term

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Abstract

Background: Children born preterm are at risk for developing reading difficulties and for decrements in other cognitive skills compared to children born at term.

Aims: To assess how domains of function, often negatively impacted by preterm birth, predict reading development in children born preterm and at term.

Study design: Longitudinal descriptive cohort study.

Subjects: Preterm ($n=48$; gestational age 22–32 weeks, 30 males) and term ($n=41$, 18 males) participants were assessed at age 6 years on a battery of verbal and non-verbal cognitive skills and reassessed at age 8 the Gray Oral Reading Tests-5. Linear regressions assessed the contributions of phonological awareness, language, executive function, and non-verbal IQ at age 6 to reading outcome at age 8.

Results: Children born preterm had lower scores than children born at term on all measures (Cohen's d from 0.46–1.08, all $p<.05$). Phonological awareness and language abilities predicted reading in both groups (accounting for 19.9% and 25.0% of variance, respectively, $p<.001$). Birth group did not moderate the association. By contrast, the association between executive function and non-verbal intelligence and reading outcome was moderated by birth group (interaction accounted for 3.9–6.7% of variance, respectively, $p<.05$). Positive predictions to reading from executive function and non-verbal IQ were found only in children born preterm.

Conclusions: Non-verbal cognitive measures improved the prediction of reading outcome only in the preterm group, suggesting that reading decrements represent a component of global deficits.

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These findings have implications for evaluation of children born preterm at school entry and treatment of reading difficulties.

Keywords

prematurity; reading development; phonological awareness; language; cognition; executive function; prediction

Introduction

Children's reading abilities are strong predictors of long-term academic and occupational success. Wide variation in reading abilities emerges at young ages and persists into adulthood. Phonological awareness, the ability to detect and manipulate sounds within words, and general language skills are generally strong predictors of reading abilities [1–4]. Instruction on phonological awareness and sound-letter mapping leads to substantial improvement in reading if provided before, but not after second grade [1,2,4]. It is critical to identify children at risk for reading difficulties in early grades to provide timely, evidence-based instruction and intervention.

Children born preterm are at increased risk for reading difficulties [5] in single word reading and reading comprehension [6]. Skills considered pivotal to reading development, including phonological awareness [7,8] and language [9,10], collectively summarized here as *verbal skills*, are weaker in children born preterm compared to term peers. Phonological awareness and language skills predict reading outcomes in children born preterm [11,12]. Reading deficits frequently co-occur along with weakness in abilities associated with, but less tightly coupled to reading abilities, including poor executive function skills [13–15] and lower general intelligence [5,16], collectively summarized here as *non-verbal cognitive skills*. Less is known about how different domains of function, negatively impacted by preterm birth, collectively predict reading development in children born preterm [7,17]. Moreover, few studies have directly compared multiple predictors of reading in children born preterm and term [12,17].

We conducted a longitudinal study of reading at age 6 to 8 years to determine which early skills would predict reading in children born preterm and at term. We evaluated verbal skills—phonological awareness and language [1,2]—and non-verbal cognitive skills—executive function [17–19] and non-verbal intelligence [20]. We had three aims: (i) To compare children born preterm and at term on verbal, non-verbal cognitive, and reading skills. We anticipated children born preterm would have poorer performance [5,16,21]. (ii) To determine if verbal skills at age 6 would predict reading at age 8 in children born preterm and at term. We hypothesized that verbal skills would predict reading in both groups because of their fundamental role in reading development in samples of children born preterm [11,12] and at term [2,22,23]. (iii) To establish whether non-verbal cognitive skills would predict reading in the children born preterm and/or at term. We hypothesized that non-verbal cognitive skills would predict reading abilities only in children born preterm, based on earlier findings showing a broader set of abilities associated with reading and academic achievement in children born preterm compared to children born at term [12,24–26].

Methods

Participants

Participants were recruited between 2012 and 2015 as part of a longitudinal cohort study that investigated reading in children born preterm. Preterm birth was defined as < 32 weeks gestational age and term-birth was defined as ≥ 37 weeks gestational age or birth weight ≥ 2,500 grams. Children were recruited from high risk infant follow-up clinics. Exclusion criteria included conditions other than prematurity that might impact learning to read, including intelligence quotient < 80, significant hearing loss or visual impairment, and non-English speakers. The term group was a convenience sample of volunteers.

We enrolled 54 children born preterm and 50 born at term. Of these, six and seven did not return for the 8-year old visit in the preterm and term groups, respectively, and were therefore excluded from this study. Two enrolled participants born at term were excluded from this analysis because of late diagnosis of specific language impairment ($n=1$) and lack of formal reading instruction ($n=1$). The final sample included 48 children born preterm (30 males, mean age at time 1: **6.13y (Standard Deviation, SD 0.19, range 5.83y-6.58y); mean age at time 2: 8.21y (SD 0.21, range 8.00y-8.67y)** and 41 children born term (18 males, mean age at time 1: **6.13y (SD 0.17, range 5.83y-6.58y); mean age at time 2: 8.10y (SD 0.14, range 8.00y-8.83y)**). A subset was included in a related study [blinded information] [27]. The experimental protocol was approved by the (blinded information) University Institutional Review Board. A parent or guardian provided informed consent; children were compensated for participation.

Parents completed demographic and health history questionnaires at enrollment. Socioeconomic status was measured using a modified version of the Hollingshead Index of Socioeconomic Status [28]; we determined social status based on one or both parents' educational and occupational attainment, depending on the family composition [27]. Participants were classified bilingual if a parent reported that their child could speak a language other than English. Inclusion criteria required that all children were fluent in English, attended English-speaking schools for at least two years prior to enrollment, and completed all assessments in English. Children were categorized as having a family history of reading delays if any first-degree relatives (mother, father, siblings) were diagnosed or suspected of having a reading disorder. Table 1 describes the sample.

Procedures

Children completed assessments of phonological awareness, language, executive function, and non-verbal IQ at age 6. Phonological awareness was measured using the Comprehensive Test of Phonological Processing (CTOPP) [22]. The Phonological Awareness Composite score consists of Elision, Blending Words, and Sound Matching subtests. Language skills were measured using the Clinical Evaluation of Language Fundamentals - Fourth Edition (CELF-4) [29]. The Core Language Index is comprised of scaled scores from Concepts and Following Directions, Word Structure, Recalling Sentences, and Formulated Sentences subtests. One child born preterm did not complete the CELF-4 because of time constraints and was not included in analyses that required this score.

Executive function was measured using Spatial Span, Spatial Working Memory, and Stockings of Cambridge from the Cambridge Neuropsychological Test Automated Battery (CANTAB) [30], a widely-used and developmentally sensitive computerized executive function battery [31]. Spatial Span assesses working memory capacity. The measure analyzed was Span Length, the longest sequence of squares recalled correctly. Spatial Working Memory assesses the ability to retain and manipulate spatial information. The measure analyzed was Total Errors, the number of times an incorrect selection was made. Stockings of Cambridge assesses response inhibition, planning, and organization skills. The measure analyzed was Problems Solved in Minimum Moves. Analyses were based on raw scores because **the research version of the CANTAB** does not use age-adjusted scores. Fortunately, the children in our sample were all about 6 years old and the two birth groups were closely matched on age. **In addition, we created z-scores for the entire sample for all three measures for analyses.** Two participants, (one preterm, one term) were missing the CANTAB because of time constraints and were not included in analyses that used these measures.

Non-verbal Intelligence Quotient was measured using the Perceptual Reasoning Index from the Wechsler Abbreviated Scale of Intelligence-II (WASI-II) [32]. Non-verbal IQ scores were derived from the Block Design and Matrix Reasoning subtests.

Children returned for the follow-up visit at age 8. Text reading, the outcome variable, was assessed using the Gray Oral Reading Tests - Fifth Edition (GORT-5) [33]. The GORT-5 measures reading by requiring children to read stories of advancing difficulty aloud and then answer questions about the passage. The Oral Reading Index (referred to as reading **outcome**) measures comprehension and fluency, comprised of accuracy and rate of reading. Mean standard scores of all assessments are shown for both birth groups in Table 1.

Statistical Analyses

All analyses were conducted using IBM SPSS software (version 23.0, IBM Corporation, 2014) with statistical significance set at $p < 0.05$. The Shapiro-Wilk test confirmed a normal distribution of behavioral measures and residuals.

Because executive function skills often function as a unitary construct in young children [34], and to reduce the number of separate analyses, we derived an executive function composite factor from three measures of executive function. We conducted principal axis factor analysis with oblique rotation (direct oblimin). The Kaiser-Meyer-Olkin (KMO) measure verified the sampling adequacy for analysis, $KMO = 0.58$, and all KMO values for individual items (0.56 to 0.69) were above the acceptable limit (33). The resulting executive function factor had an eigenvalue $>$ Kaiser's criterion of 1 and explained 31% of the variance. **We repeated the factor analysis with the z-scores for all three measures and the results were identical.**

To evaluate possible factors confounded with birth group, two-tailed independent t-tests compared reading outcome at age 8 in the following subgroups: male versus female, monolingual versus bilingual, and kindergarten versus first grade. Mann-Whitney U tests compared reading outcome for subgroups with uneven sample sizes: positive versus negative

family history of reading delays and kindergarten versus first grade. Pearson correlations assessed the degree of association between reading outcome at age 8 and socioeconomic status, phonological awareness, language, executive function, and non-verbal IQ at age 6. We applied Bonferroni corrections to account for multiple comparisons.

To assess the contribution of verbal and non-verbal cognitive skills at age 6 to reading outcome at age 8, we performed a series of linear regressions. Demographic variables that showed subgroup differences or associations with reading outcome were covariates in all models. We independently evaluated the predictive value of phonological awareness and core language. To determine whether birth group status moderated the prediction, we entered interaction terms following each subskill. We repeated linear regressions using the executive function factor and non-verbal IQ as predictors and interaction terms to assess moderation. We assessed the unique contribution of executive function and non-verbal IQ after consideration of phonological awareness and core language. We assessed multicollinearity using the variance inflation factor (VIF). We considered a VIF less than 10 to indicate an acceptable level of multicollinearity [35,36]. We also centered the data. To display differences in the contribution of predictive variables to reading outcome, we repeated regression models in the children born preterm and at term separately. Venn diagrams using the Pacific Northwest National Laboratory software [37] were used to display the amount of unique variance accounted for by each predictor set as circles, varying in size for the strength of prediction, and shared variance as overlap between the circles. Finally, we assessed which of the three executive function tasks uniquely contributed to reading outcome using separate regression analyses in each birth group.

Results

Children born preterm had lower mean scores on all assessments at age 6 and on reading outcome at age 8 compared to children born at term (Table 1). Mean scores for both groups **on standardized measures** fell within the normal range. Boys had lower mean reading scores than girls; reading outcome did not differ as a function of family history of reading delays, bilingual status, or grade (Table A). Socioeconomic status was positively associated with reading outcome across the sample, $r(87)=0.29$, $p=.005$. Therefore, we included sex and socioeconomic status as covariates in all regression models. Reading outcome at age 8 was significantly associated with phonological awareness, core language, executive function, and non-verbal IQ at age 6 across the sample (Table B). Correlations across verbal and non-verbal cognitive predictor variables ranged from 0.19 to 0.64, below the level of concern for multicollinearity [36]. Further, no VIF values exceeded 2.5; therefore, there was no concern regarding multicollinearity.

Table 2 shows the results of multiple regression models predicting reading outcome at age 8 by verbal skills at age 6. *Model 1A* shows that sex, socioeconomic status, and birth group status accounted for approximately 15% of the variance in reading outcome. When controlling for sex and socioeconomic status, birth group was not a significant predictor of reading outcome. *Model 1B* revealed that phonological awareness added almost 20% unique variance compared to *Model 1A*. *Model 1C* introduced the interaction between birth group and phonological awareness and indicated no increase in variance accounted for. Thus, the

relation between phonological awareness and reading outcome was comparable in both groups, illustrated in Figure 1A. *Model 1D* showed that core language contributed significant unique variance to reading outcome, accounting for 25% additional variance compared to *Model 1A*. In *Model 1E*, the addition of the interaction term did not increase overall model fit indicating that this relation was comparable in both groups, illustrated in Figure 1B.

Table 3 shows the results of multiple regression models predicting reading outcome at age 8 by non-verbal cognitive skills at age 6. *Model 2A* is identical to *Model 1A*. *Model 2B* showed that executive function did not significantly contribute to reading outcome. However, *Model 2C* showed a significant interaction with birth group status, contributing approximately 4% additional variance. The prediction of executive function to reading outcome was positive in the preterm, but not term group, illustrated in Figure 1C. In *Model 2D*, non-verbal IQ contributed approximately 8% additional variance compared to *Model 1A*. *Model 2E* showed that this prediction was moderated by birth group status, illustrated in Figure 1D. Non-verbal IQ predicted reading outcome in the preterm, but not term group.

Table C shows regression models of the combined prediction of verbal and non-verbal cognitive skills to reading outcome. These analyses confirmed that the relation between executive function and non-verbal IQ and reading outcome was moderated by birth group status even after consideration of verbal skills. Table D compares the pattern of prediction for all variables in preterm and term groups separately. The only unique predictor of reading outcome in the preterm group was non-verbal IQ, whereas the only unique predictor in the term group was phonological awareness. Figure 2 displays unique versus shared variance of predictors within the birth groups separately. Non-verbal cognitive skills represent a larger proportion of the variance in reading in the preterm group whereas verbal skills represent a larger proportion of the variance in reading in the term group. We further investigated which task within the executive function battery was driving the prediction in children born preterm. We found that Spatial Span Length was the sole unique contributor to reading outcome in the preterm group (Table E).

Discussion

Children born preterm performed significantly lower than children born at term on all predictors at age 6 and reading at age 8. These findings are consistent with the literature [5,6,9,10,16,38,39]. We confirmed that verbal skills—phonological awareness and core language—at age 6 predicted reading at age 8 in both groups. In contrast, non-verbal cognitive measures—executive function and non-verbal IQ—improved the prediction of reading outcome in children born preterm but not children born at term. Based on these results, we inferred that children born preterm relied on a broader set of early skills to achieve fluent text reading than do children born at term [25,40].

We replicated previous studies that found that phonological processing predicted later reading in children born preterm [11,12]. While language was previously found to be a weaker predictor of reading in children born preterm than term [41], we demonstrated that language skills were comparable predictors of reading in both birth groups. These results

were not surprising. Reading familiar and unfamiliar words in an alphabetic language, like English, requires the ability to segment auditory words into constituent phonemes, the sub-word units of sound that distinguish one word from another, and to link phonemes with letters of the written language. Further, phonological awareness has been found to be associated with general language abilities [42]. Regardless of birth group status, learning to read relied on the same **verbal** prerequisites.

We found that an executive function factor and non-verbal IQ predicted reading outcome in children born preterm but not in children born at term. In children born preterm, executive function deficits have previously been associated with reading disorders [17]. In this study, when individual components of the executive function factor were assessed in relation to reading outcome, Spatial Span Length was the only unique predictor in the children born preterm (Table E). Spatial Span Length indexes spatial capacity and is a visuo-spatial analogue of the digit span task. Its relation to later reading may arise because it assesses working memory capacity while eliminating the auditory and verbal confounding factors. We recognize that other studies evaluating children born at term vary in the degree of association between non-verbal cognitive skills and reading abilities based on study design, such as age and task [43–45]. It is possible that we did not detect longitudinal associations between executive function and reading outcome in the term sample because of the specific measures we selected. Broadly, the CANTAB taps into spatial and working memory, organization, and planning. Other measures of executive function might have predicted reading outcome in children born at term. The lack of findings in the term group may also have related to the young age of these participants or assessing early executive function skills as predictors of later reading abilities rather than as correlates of concurrent reading skills. Finally, the sample size may not have been sufficiently large to detect prediction in the term group. However, if the main problem was the sample size, it nonetheless indicated that **associations with reading in the term group were stronger for verbal than for non-verbal cognitive skills.**

When covariates, verbal skills, and non-verbal cognitive skills were evaluated simultaneously in each birth group, non-verbal IQ was the sole unique predictor of text reading in children born preterm. These findings suggested that reading decrements in children born preterm represented a component of global deficits. An explanation for this distinctive pattern of prediction is that reading difficulties in children born preterm represent the cumulative effect of many neuropsychological factors, including early brain abnormalities [46] and multiple neuropsychological weaknesses, such as slow speed of processing [47], weak verbal working memory [48], deficits in oral language [9,10], and decreased intelligence [16].

Children born preterm and at term have been demonstrated to show similar associations of phonological awareness skills and microstructural properties of the arcuate fasciculus [27], a white matter pathway that is highly associated with reading skills in children born at term [49–52]. However, children born preterm did not show the association between language skills and the uncinate fasciculus that was found in children born at term [27]. Taken together, these findings suggest that differing performance on reading-related measures and

contrasting patterns of prediction to later reading across birth groups may be related to both neurobiological and neuropsychological factors.

This study has several clinical implications for care of children born preterm. Monitoring progress of children born preterm should continue at least until they enter school because they remain at high risk for academic problems (5,16,22,46). Early assessment of children born preterm for reading difficulties should include measures of phonological awareness and language abilities, as these **verbal** skills accounted for substantial variance in later reading abilities. Since executive function skills and non-verbal intelligence improved the prediction of reading, these general domains of functioning should also be included in assessments of children born preterm. Assessing the preterm child's status in non-verbal cognitive skills may prove useful in designing effective instruction and interventions to improve reading outcomes. Because children born preterm had global deficits, training only in phonological awareness and early reading skills might prove less effective than such training for children born at term. Children born preterm may require enhanced training of reading prerequisites and/or supplemental training in cognitive areas, such as executive function [55,56]. Finally, with parent permission, educators should be made aware of a child's preterm status. If teachers understand that academic difficulties among children born preterm are global, they may plan strategies to support multiple cognitive domains of relative weakness.

Limitations

The study sample was a convenience sample, modest in size. The mean socioeconomic status was high, which may result in more favorable outcomes and limit the generalizability to other samples. Children born preterm had lower socioeconomic status than children born at term, though the difference was not statistically significant and socioeconomic status was a covariate in all regression models. We measured executive function using a battery of computerized tasks. Previous studies have found that laboratory tests in isolation may miss children whose parents report that they have executive function deficits [57]. Further, we observed group differences between children born preterm and at term on all predictor variables of phonological awareness, language, executive function, and non-verbal IQ.

Potential differences in the association of non-verbal cognitive skills with reading at different levels of ability may have contributed to these differences in associations.

Future work should examine whether the interactions between birth groups replicate in a sample of children born preterm and at term matched on performance.

Conclusion and Future Directions

Whereas phonological awareness and language abilities at age 6 predicted reading at age 8 in both groups, executive function and non-verbal intelligence skills predicted later reading only in children born preterm. If reading deficits in children born preterm are, in fact, one component of a global deficit, future research should assess the efficacy of standard reading interventions in children born preterm who are struggling with learning to read. Clinicians and educators need to know whether children born preterm benefit from similar remedial instruction as children born at term in order to support their reading development accordingly. Based on our findings, it is likely that comprehensive training including both

verbal and non-verbal cognitive skills may be needed for children born preterm, whereas targeted training in verbal skills may be sufficient for children born at term. Early training in global abilities, such as executive function, may act as a protective factor against poor reading in children born preterm. A customized educational approach for children born preterm would serve as an important example of Precision Medicine and Education.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

- [1]. Developing Early Literacy: Report of the National Early Literacy Panel. vol. 2 Jessup, Maryland 20794–1398.: 2008. doi:10.1598/RRQ.45.1.2.
- [2]. National Reading Panel. Teaching children to read: An evidence-based assessment of the scientific research literature on reading and its implications for reading instruction. NIH Publ No 00–4769 2000;7:35. doi:10.1002/ppul.1950070418.
- [3]. Hulme C, Bowyer-Crane C, Carroll JM, Duff FJ, Snowling MJ. The Causal Role of Phoneme Awareness and Letter-Sound Knowledge in Learning to Read: Combining Intervention Studies With Mediation Analyses. *Psychol Sci* 2012;23:572–7. doi:10.1177/0956797611435921. [PubMed: 22539335]
- [4]. Connor CM, Alberto PA, Compton DL, O'Connor RE. Improving Reading Outcomes for Students with or at Risk for Reading Disabilities: A Synthesis of the Contributions from the Institute of Education Sciences Research Centers. NCSER 2014–3000. *Natl Cent Spec Educ Res* 2014;108.
- [5]. Aarnoudse-Moens CSH, Weisglas-Kuperus N, van Goudoever JB, Oosterlaan J. Meta-analysis of neurobehavioral outcomes in very preterm and/or very low birth weight children. *Pediatrics* 2009;124:717–28. doi:10.1542/peds.2008-2816. [PubMed: 19651588]
- [6]. Kovachy VN, Adams JN, Tamaresis JS, Feldman HM. Reading abilities in school-aged preterm children: A review and meta-analysis. *Dev Med Child Neurol* 2015;57. doi:10.1111/dmcn.12652.
- [7]. Guarini A, Sansavini A, Fabbri C, Alessandrini R, Faldella G, Karmiloff-Smith A. Reconsidering the impact of preterm birth on language outcome. *Early Hum Dev* 2009;85:639–45. doi:10.1016/j.earlhumdev.2009.08.061. [PubMed: 19748193]
- [8]. Mullen KM, Vohr BR, Katz KH, Schneider KC, Lacadie C, Hampson M, et al. Preterm birth results in alterations in neural connectivity at age 16 years. *Neuroimage* 2011;54:2563–70. doi: 10.1016/j.neuroimage.2010.11.019. [PubMed: 21073965]
- [9]. Barre N, Morgan A, Doyle LW, Anderson PJ. Language abilities in children who were very preterm and/or very low birth weight: a meta-analysis. *J Pediatr* 2011;158:766–774.e1. [PubMed: 21146182]
- [10]. van Noort-van der Spek IL, Franken MC, Weisglas-Kuperus N. Language functions in preterm-born children: a systematic review and meta-analysis. *Pediatrics* 2012;129:745–54. [PubMed: 22430458]

- [11]. Wocadlo C, Rieger I. Phonology, rapid naming and academic achievement in very preterm children at eight years of age. *Early Hum Dev* 2007;83:367–77. doi:10.1016/j.earlhumdev.2006.08.001. [PubMed: 16979856]
- [12]. Johnson S, Wolke D, Hennessy E, Marlow N. Educational outcomes in extremely preterm children: Neuropsychological correlates and predictors of attainment. *Dev Neuropsychol* 2011;36:74–95. doi:10.1080/87565641.2011.540541. [PubMed: 21253992]
- [13]. Loe IM, Lee ES, Luna B, Feldman HM. Executive function skills are associated with reading and parent-rated child function in children born prematurely. *Early Hum Dev* 2012;88:111–8. doi:10.1016/j.earlhumdev.2011.07.018. [PubMed: 21849240]
- [14]. Alduncin N, Huffman LC, Feldman HM, Loe IM. Executive function is associated with social competence in preschool-aged children born preterm or full term. *Early Hum Dev* 2014;90. doi:10.1016/j.earlhumdev.2014.02.011.
- [15]. Loe IM, Feldman HM, Huffman LC. Executive function mediates effects of gestational age on functional outcomes and behavior in preschoolers. *J Dev Behav Pediatr* 2014;35. doi:10.1097/DBP.0000000000000063.
- [16]. Bhutta AT, Cleves MA, Casey PH, Cradock MM, Anand KJS. Cognitive and Behavioral Outcomes of School-Aged Children Who Were Born Preterm. *Jama* 2002;288:728. doi:10.1001/jama.288.6.728. [PubMed: 12169077]
- [17]. Frye RE, Landry SH, Swank PR, Smith KE. Executive Dysfunction in Poor Readers Born Prematurely at High Risk. *Dev Neuropsychol* 2009;34:254–71. doi:10.1080/87565640902805727. [PubMed: 19437202]
- [18]. Sesma H, Mahone E, Levine T, Eason S, Cutting L. The contribution of executive skills to reading comprehension. *Child Neuropsychol* 2009;15:232–46. [PubMed: 18629674]
- [19]. Cameron CE, Brock LL, Murrah WM, Bell LH, Worzalla SL, Grissmer D, et al. Fine Motor Skills and Executive Function Both Contribute to Kindergarten Achievement. *Child Dev* 2012;83:1229–44. doi:10.1111/j.1467-8624.2012.01768.x. [PubMed: 22537276]
- [20]. Silva PA, McGee R, Williams SM. Developmental Language Delay from Three to Seven Years and its Significance for Low Intelligence and and REading Difficulties at age Seven. *Dev Med Child Neurol* 2008;25:783–93. doi:10.1111/j.1469-8749.1983.tb13847.x.
- [21]. Aylward GP. Update on Neurodevelopmental Outcomes of Infants Born Prematurely. *J Dev Behav Pediatr* 2014;35:392–3. [PubMed: 25007062]
- [22]. Wagner R, Torgesen J, Rashotte CA. Comprehensive test of phonological processes (CTOPP). Austin, TX: Pro-Ed; 1999.
- [23]. Wagner R, Torgesen J, Rashotte C, Pearson N. Comprehensive Test of Phonological Processing, Second Edition (CTOPP-2). San Antonio, TX: Pearson Education Inc.; 2013.
- [24]. Ortiz-Mantilla S, Choudhury N, Leever H, Benasich AA. Understanding language and cognitive deficits in very low birth weight children. *Dev Psychobiol* 2008;50:107–26. doi:10.1002/dev.20278. [PubMed: 18286580]
- [25]. Anderson PJ. Neuropsychological outcomes of children born very preterm. *Semin Fetal Neonatal Med* 2014;19:90–6. [PubMed: 24361279]
- [26]. Johnson S, Hennessy E, Smith R, Trikic R, Wolke D, Marlow N. Academic attainment and special educational needs in extremely preterm children at 11 years of age: the EPICure study. *Arch Dis Child Fetal Neonatal Ed* 2009;94:F283–9. doi:10.1136/adc.2008.152793. [PubMed: 19282336]
- [27]. Dodson CK, Travis KE, Borchers LR, Marchman VA, Ben-Shachar M, Feldman HM. White matter properties associated with pre-reading skills in 6-year-old children born preterm and at term. *Dev Med Child Neurol* 2018;60:695–702. doi:10.1111/dmcn.13783. [PubMed: 29722009]
- [28]. Hollingshead A Four factor index of social status. New Haven, CT: Yale University Press; 1975.; 1975.
- [29]. Semel-Mintz E, Wiig ESW. Clinical Evaluation of Language Fundamentals. 4. San Antonio: Psychological Corporation; 2003.
- [30]. CANTAB Research Grant | Terms and Conditions | Cambridge Cognition n.d. <http://www.cambridgecognition.com/cantab-research-grant-terms-and-conditions/> (accessed August 22, 2018).

- [31]. Luciana M Practitioner Review: Computerized assessment of neuropsychological function in children: clinical and research applications of the Cambridge Neuropsychological Testing Automated Battery (CANTAB). *J Child Psychol Psychiatry* 2003;44:649–63. doi: 10.1111/1469-7610.00152. [PubMed: 12831110]
- [32]. Wechsler D Wechsler Abbreviated Scale of Intelligence. 2nd dition San Antonio, TX: Pearson; 2011.
- [33]. Wiedeholt J, Bryant B. Gray Oral Reading Test, Fifth Edition Autstin TX: Pro-Ed Inc.; 2012.
- [34]. Wiebe SA, Espy KA, Charak D. Using confirmatory factor analysis to understand executive control in preschool children: I. Latent structure. *Dev Psychol* 2008;44:575–87. doi: 10.1037/0012-1649.44.2.575. [PubMed: 18331145]
- [35]. Kutner MH, Nachtsheim CJ, Neter J, Li W. Applied Linear Statistical Models, Fifth Edition Fifth. Boston: McGraw-Hill Irwin; 2005.
- [36]. Field A Discovering statistics using IBM SPSS statistics. sage; 2013.
- [37]. Integrative Omics | Pacific Northwest National Laboratory n.d. <https://omics.pnl.gov/> (accessed September 5, 2018).
- [38]. Mullen KM, Vohr BR, Katz KH, Schneider KC, Lacadie C, Hampson M, et al. Preterm birth results in alterations in neural connectivity at age 16 years. *Neuroimage* 2011;54:2563–70. doi: 10.1016/j.NEUROIMAGE.2010.11.019. [PubMed: 21073965]
- [39]. Lee ES, Yeatman JD, Luna B, Feldman HM. Specific language and reading skills in school-aged children and adolescents are associated with prematurity after controlling for IQ. *Neuropsychologia* 2011;49:906–13. doi:10.1016/j.neuropsychologia.2010.12.038. [PubMed: 21195100]
- [40]. Wolke D, Meyer R. Cognitive status, language attainment, and prereading skills of 6-year-old very preterm children and their peers. *Dev Med Child Neurol* 1999;41:94–109. [PubMed: 10075095]
- [41]. Frye R, Landry S, Swank P, Smith K. Executive dysfunction in poor readers born prematurely at high risk. *Dev Neuropsychol* 2009;34:254–71. [PubMed: 19437202]
- [42]. Lonigan CJ, Burgess SR, Anthony JL. Development of emergent literacy and early reading skills in preschool children: Evidence from a latent-variable longitudinal study. *Dev Psychol* 2000;36:596–613. doi:10.1037/0012-1649.36.5.596. [PubMed: 10976600]
- [43]. Ferrer E, Shaywitz BA, Holahan JM, Marchione K, Shaywitz SE. Uncoupling of reading and IQ over time: Empirical evidence for a definition of dyslexia. *Psychol Sci* 2010;21:93–101. doi: 10.1177/0956797609354084. [PubMed: 20424029]
- [44]. Fricke S, Bowyer-Crane C, Haley AJ, Hulme C, Snowling MJ. Efficacy of language intervention in the early years. *J Child Psychol Psychiatry Allied Discip* 2013;54:280–90. doi:10.1111/jcpp.12010.
- [45]. Hulme C, Snowling M. The interface between spoken and written language: developmental disorders. *Philos Trans R Soc London - Ser B Biol Sci* 2014;369:20120395. [PubMed: 24324239]
- [46]. Volpe JJ. Brain injury in premature infants : a complex amalgam of destructive and developmental disturbances. *Lancet Neurol* 2009;8:110–24. doi:10.1016/S1474-4422(08)70294-1. [PubMed: 19081519]
- [47]. Loi EC, Marchman VA, Fernald A, Feldman HM. Using Eye Movements to Assess Language Comprehension in Toddlers Born Preterm and Full Term. *J Pediatr* 2017;180. doi:10.1016/j.jpeds.2016.10.004.
- [48]. Gresch LD, Marchman VA, Loi EC, Fernald A, Feldman HM. Nonword repetition and language outcomes in young children born preterm. *J Speech, Lang Hear Res* 2018;61. doi: 10.1044/2018_JSLHR-L-17-0217.
- [49]. Yeatman JD, Dougherty RF, Rykhlevskaia E, Sherbondy AJ, Deutsch GK, Wandell BA, et al. Anatomical Properties of the Arcuate Fasciculus Predict Phonological and Reading Skills in Children. *J Cogn Neurosci* 2011;23:3304–17. doi:10.1162/jocn_a_00061. [PubMed: 21568636]
- [50]. Ben-shachar M, Dougherty RF, Wandell BA. White matter pathways in reading 2007:258–70. doi:10.1016/j.conb.2007.03.006.

- [51]. Vanderauwera J, Vandermosten M, Dell'Acqua F, Wouters J, Ghesquière P. Disentangling the relation between left temporoparietal white matter and reading: A spherical deconvolution tractography study. *Hum Brain Mapp* 2015. doi:10.1002/hbm.22848.
- [52]. Vandermosten M, Boets B, Poelmans H, Sunaert S, Wouters J, Ghesquière P. A tractography study in dyslexia: Neuroanatomic correlates of orthographic, phonological and speech processing. *Brain* 2012;135:935–48. doi:10.1093/brain/awr363. [PubMed: 22327793]
- [53]. Aylward GP. Neurodevelopmental outcomes of infants born prematurely. *J Dev Behav Pediatr* 2005;26:394–407. doi:10.1097/01.DBP.0000452240.39511.d4.
- [54]. Taylor HG, Klein N, Anselmo MG, Minich N, Espy KA, Hack M. Learning Problems in Kindergarten Students With Extremely Preterm Birth. *Arch Pediatr Adolesc Med* 2011;165:819. doi:10.1001/archpediatrics.2011.137. [PubMed: 21893648]
- [55]. Løhaugen GCC, Antonsen I, Håberg A, Gramstad A, Vik T, Brubakk AM, et al. Computerized working memory training improves function in adolescents born at extremely low birth weight. *J Pediatr* 2011;158. doi:10.1016/j.jpeds.2010.09.060.
- [56]. Grunewaldt KH, Løhaugen GCC, Austeng D, Brubakk A-M, Skranes J. Working memory training improves cognitive function in VLBW preschoolers. *Pediatrics* 2013;131:e747–54. doi: 10.1542/peds.2012-1965. [PubMed: 23400616]
- [57]. Loe IM, Chatav M, Alduncin N. Complementary Assessments of Executive Function in Preterm and Full Term Preschoolers. *Child Neuropsychol A J Norm Abnorm Dev Child Adolesc* 2015;21:331–53.

Highlights

- Phonological awareness and language skills at age 6 similarly predicted reading at age 8 in children born preterm and term
- Executive function and non-verbal intelligence at age 6 predicted reading at age 8 only in the preterm group.
- Reading decrements in preterm group likely represented one component of global deficits.

Figure 1.

Regression residuals of **verbal** and **non-verbal cognitive** predictors at age 6 and reading outcome at 8 in children born preterm (PT) and at term (FT). Figures 1A-1B show similar prediction to reading across groups, represented by straight lines. Figures 1C-1D demonstrate an interaction, represented by crossing lines. Change () in the variance accounted for (R^2) represent increased variance explained by each predictor variable after consideration of covariates.

* $p < .05$, ** $p < .01$, *** $p < .001$

Figure 2:
Venn Diagrams visualizing the unique and shared variance of the verbal and non-verbal cognitive predictor variables in relation to reading outcome in children born preterm and at term.

Table 1.

Characteristics of the sample

<i>N</i> = 89	Preterm (<i>n</i> = 48) <i>M</i> (SD) or <i>n</i>	Term (<i>n</i> = 41) <i>M</i> (SD) or <i>n</i>	<i>t</i> or χ^2	<i>p</i>	Cohen's <i>d</i>
<i>Demographic Measures</i>					
Age at time 1 (years)	6.13 (0.19)	6.13 (0.17)	0.19	.848	0.00
Birth weight (grams)	1,282 (432.03)	3,303 (411.98)	22.48	.001	4.79
Gestational age at birth (weeks)	29.23 (2.15)	39.51 (1.53)	25.59	.001	5.51
White #	33	29	0.04	.839	n/a
Males #	30	18	3.08	.079	n/a
Family History of RD ^a	3	8	3.59	.058	n/a
Kindergarten #	38	28	1.36	.243	n/a
SES ^b at age 6	53.84(13.24)	58.61 (9.60)	1.96	.053	0.41
<i>Verbal, non-verbal cognitive, and reading measures</i>					
Phonological awareness ^c age 6	108.15 (12.84)	113.88 (11.96)	2.17	.033	0.46
Core language ^d age 6	99.43 (12.77)	112.95 (12.36)	5.03	.001	1.08
Executive function factor ^e age 6	−0.21 (0.83)	0.24 (0.63)	2.85	.005	0.61
Span Length score ^f age 6	3.60 (1.36)	4.28 (0.96)	−2.64	.010	0.58
Total Errors score ^g age 6	64.79 (15.66)	57.85 (14.91)	2.12	.037	0.45
Problems Solved score ^h age 6	3.70 (1.27)	3.95 (1.12)	−0.97	.334	0.21
Non-verbal IQ ⁱ age 6	98.52 (12.77)	113.63 (15.92)	4.97	.001	1.05
Reading outcome ^j age 8	96.00 (10.83)	101.54 (12.70)	2.22	.029	0.47

^aFamily history of reading delays^bSocioeconomic status, measured with the Hollingshead Index^cPhonological Awareness Composite, measured with the CTOPP^dCore Language Index, measured with the CELF-4^eExecutive function factor, measured with the CANTAB^fDerived from Spatial Span subtest from the CANTAB^gDerived from Spatial Working Memory subtest from the CANTAB^hDerived from Stockings of Cambridge subtest from the CANTABⁱPerceptual Reasoning Index, measured with the WASI-II^jOral Reading Index, measured with the GORT-5

Table 2.

Prediction of reading outcome at age 8 by phonological awareness and core language at age 6 years, controlling for sex and socioeconomic status, in children born preterm and at term ($n = 89$) (Unstandardized Coefficients; SE).

	Model 1A	Model 1B	Model 1C	Model 1D	Model 1E
Sex	4.59 (2.43)	2.72 (2.17)	2.72 (2.18)	1.08 (2.14)	1.05 (2.17)
SES^a	0.26 (0.10) *	0.19 (0.09) *	0.18 (0.09) *	0.06 (0.09)	0.06 (0.10)
Group	-3.46 (2.48)	-1.60 (2.21)	-0.35 (19.44)	1.93 (2.31)	3.90 (17.94)
Phono aware^b	-	0.44 (0.09) ***	0.45 (0.13) ***	-	-
Phono aware x Group	-	-	-0.01 (0.17)	-	-
Language^c	-	-	-	0.53 (0.09) ***	0.54 (0.13) ***
Language x Group	-	-	-	-	-0.02 (0.17)
R²	-	19.9% ***	0.0%	25.0% ***	0.0%
Total R²	15.2% **	35.2% ***	35.2% ***	40.6% ***	40.6% ***

^a Socioeconomic status, measured with the Hollingshead Index

^b Phonological Awareness Composite, measured with the CTOPP

^c Core Language Index, measured with the CELF-4

* $p < .05$,

** $p < .01$,

*** $p < .001$

Table 3.

Prediction of reading outcome by executive function and non-verbal IQ, controlling for sex and socioeconomic status, in children born preterm and at term ($n = 89$) (Unstandardized Coefficients; SE).

	Model 2A	Model 2B	Model 2C	Model 2D	Model 2E
Sex	4.59 (2.43)	3.96 (2.46)	3.32 (2.43)	3.60 (2.36)	3.55 (2.27)
SES^a	0.26 (0.10) *	0.23 (0.10) *	0.24 (0.10) *	0.15 (0.11)	0.14 (0.10)
Group^b	-3.46 (2.48)	-2.13 (2.53)	-2.85 (2.51)	-0.38 (2.61)	-46.60 (16.68) **
EF factor^c	-	3.05 (1.65)	-1.52 (2.77)	-	-
EF factor x Group	-	-	6.87(3.37) *	-	-
Non-verbal IQ^d	-	-	-	0.25 (0.09) **	0.06 (0.11)
Non-verbal IQ x Group	-	-	-	-	0.44 (0.16) **
R²	-	3.4%	3.9% *	7.5% **	6.7% **
Total R²	15.2% **	19.3% ***	23.3% ***	22.8% ***	29.5% ***

^aSocioeconomic status, measured with the Hollingshead Index

^bBirth group

^cExecutive function factor, measured with the CANTAB

^dPerceptual Reasoning Index, measured with the WASI-II

*
p < .05,

**
p < .01,

p < .001