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Effects of extreme prematurity on numerical skills and executive function in kindergarten children: An application of partially ordered classification modeling

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ABSTRACT

Although mathematics disabilities (MD) are common in extremely preterm/extremely low birth weight (EPT/ELBW) children, little is known about the nature of these problems. In this study partially ordered set (POSET) models were applied to classify 140 EPT/ELBW kindergarten children (gestational age < 28 weeks and/or birth weight < 1000 g) and 110 normal birth weight (NBW) controls into profiles of numerical and cognitive skills. Models based on five numerical skills and five executive function and processing speed skills provided a good fit to performance data. The EPT/ELBW group had poorer skills in all areas than NBW controls but the models also revealed substantial individual variability in skill profiles. Weaknesses in executive function were associated with poorer mastery of numerical skills. The findings illustrate the applicability of POSET models to research on MD and suggest distinct types of early numerical deficits in EPT/ELBW children that are related to their impairments in executive function.

1. Introduction

Many children with very preterm birth [gestational age (GA) < 32 weeks] or very low birth weight (< 1500 g) have some form of cognitive, learning, or behavioral disorder (Aylward, 2005; Hack et al., 2005; Simms et al., 2013). Mathematics disabilities (MD) are especially common in these children relative to term-born, normal birth weight (NBW) peers and cannot be fully accounted for by global reductions in cognitive ability (Simms, Cragg, Gilmore, Marlow and Johnson, 2013; Taylor, Espy, & Anderson, 2009). Very preterm children also have deficits in cognitive skills closely associated with mathematics achievement, such as executive function and processing speed (Mulder, Pitchford, & Marlow, 2010).

However, we know little about the nature of MD in these children. Most studies that have examined MD in preterm samples have administered standardized tests that assess composites of mathematics skills (Simms et al., 2013; Taylor et al., 2009). Reliance on these omnibus measures precludes identification of the types of mathematics skills adversely affected by prematurity. At early school age these "domain-specific" skills include rapid recognition of small quantities (i.e., subitizing), counting, simple addition and subtraction, recognition of numerals, and matching of number sets to numerals (Fuchs, Geary et al., 2010a; Geary, 2011a; Guarini et al., 2014; Simms et al., 2015).

1.1. Recent studies of early numerical skills in preterm children

In their study of early numerical skills, Guarini et al. (2014) compared preterm groups of 6- and 8-year-olds (GA ≤33 weeks) to age-matched controls on magnitude comparison tasks (identification of the larger of two sets of dots or Arabic digits) and on several measures of early number knowledge. Despite the absence of group differences in IQ, the younger preterm group was slower and less accurate than the controls on some of the magnitude comparison tasks and did less well on tests of number knowledge. Most of these differences were no longer evident at the older age level; the older preterm group had slower response times than their controls on some of the magnitude estimation tasks but this difference was attributed to a deficit in processing speed rather than in number sense.

In a related study, Simms et al. (2015) compared a group of 8- to 10-year-old very preterm children (GA <32 weeks) to term controls on

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tests of several specific mathematics skills as well as on measures of domain-general cognitive abilities. The preterm group had lower scores on multiple tests of early numerical skills. Differences in digit recognition, counting, and arithmetic strategies remained when controlling for non-verbal IQ. In contrast, these differences were not significant when controlling for working memory and visuospatial skills, suggesting that these cognitive abilities were contributing to the preterm group's lower test scores.

1.2. Domain-general cognitive correlates of mathematics disabilities

Findings from the latter study also highlight the importance of examining cognitive correlates of MD in preterm children. Measures of processing speed and executive function, including working memory, inhibition, and cognitive flexibility/set shifting, are among the "domain-general" cognitive functions most closely related to mathematics achievement in the general population of school-age children (Blair & Razza, 2007; Bull, Espy & Weibe, 2008; Bull & Scerif, 2001; Berg, 2008; Cirino, 2011; Clark, Pritchard, & Woodward, 2010; Clark, Sheffield, Wiebe & Espy, 2013; Espy, Bull, Martin, & Stroup, 2006; Fuchs et al., 2006; Geary, 2011a, 2011b; Gilmore et al., 2013; Simmons, Willis, & Adams, 2012). Additional predictors include phonological short-term memory and attention (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; LeFevre et al., 2010; Meyer, Salimpoor, Geary, & Minon, 2010). Several studies document associations of specific cognitive abilities in young children with mathematics competencies. Examples include studies showing associations of auditory working memory and phonological processing with the ability to solve single-digit addition problems in 5- to 6-year-olds (Simmons et al., 2012), associations of inhibition in preschoolers with later mathematics skills (Blair & Razza, 2007; Clark et al., 2010), and prediction of magnitude estimation in kindergarteners from earlier measures working memory (Kolkman, Hoijtink, Kroesbergen, & Leseman, 2013).

1.3. Study aims and the applicability of partially ordered set (POSET) models

The primary aims of this study were to examine early numerical skills, related cognitive abilities, and their association in a sample of extremely preterm/extremely low birth weight (EPT/ELBW, GA < 28 weeks and/or birth weight < 1000 g) children and NBW controls assessed during their first year of formal schooling (kindergarten). The children were recruited for a study of early school-age outcomes of extreme prematurity. Previous reports document deficits in the EPT/ELBW group relative to NBW classmates on measures of mathematics achievement and domain-general cognitive skills, including assessments of processing speed, executive function, and attention (Orchinik et al., 2011; Taylor et al., 2011). Because scores on mathematics tests represented skill composites it was unclear how component skills were affected by extreme prematurity. Additionally, distinctions between different aspects of executive function (e.g., working memory, inhibition, set shifting) were based on assumptions about test content that were not subjected to empirical confirmation. The previous reports also failed to examine associations between MD and domain-general cognitive deficits.

To address these limitations, partially ordered set (POSET) model classification methods (Jaeger, Tatsuoka, Berns, & Varadi, 2006; C. Tatsuoka, 2002; C. Tatsuoka, 2014; C. Tatsuoka & Ferguson, 2003; Tatsuoka, Tseng, et al., 2013, Tatsuoka, Varadi & Jaeger, 2013) were applied to test a model of the numerical skills contributing to children's performance on individual test items from a mathematics achievement test. Based on item content, these skills included subitizing, counting more than four objects (cardinality), and single-digit subtraction and addition. This same approach was applied in modeling aspects of domain-general cognitive skills related to mathematics achievement. Although deficits in multiple skills contribute to MD, emphasis was placed on executive function because of the strong association of this ability domain with numerical abilities in preterm children (LeFevre et al., 2010; Simms et al., 2013). Modeling of both domains in parallel made it possible to examine associations of the numerical and cognitive skills.

A major advantage of POSET models is that they explicitly acknowledge the polyfactorial nature of test performance, with multiple skills making varying contributions to performance on any given test item or score. Posterior probabilities of "state" membership, representing skill profiles into which children are classified, are computed based on test performance across different items or tests. The states are partially ordered by skill sets, ranging from states in which all or most skills are mastered to states in which no skill is mastered. One state is considered at a higher level than another if it subsumes all the mastered skills of the other state.

1.4. Hypotheses

We hypothesized that POSET modeling of early numerical skills and associated cognitive skills would reveal generalized deficiencies in the EPT/ELBW group compared to NBW controls, as well as heterogeneity of skill profiles within the EPT/ELBW group (Simms et al., 2013; Taylor et al., 2009). We further hypothesized that domain-specific numerical skills would be positively associated with domain-general cognitive skills (Berg, 2008; Bull, Espy, & Weibe, 2008; Cirino, 2011; De Smedt, Verschaffel, & Ghesquiere, 2009; Fuchs et al., 2006).

2. Material and methods

2.1. Participants

As described in previous reports (Orchinik et al., 2011; Taylor et al., 2011), 148 EPT/ELBW children without congenital conditions unrelated to preterm birth were recruited from cohorts born 2001–2003 and treated in the neonatal intensive care unit of Rainbow Babies & Children's Hospital in Cleveland, Ohio. Fifty additional survivors were not recruited because of refusals, residence outside the region, failure to locate families, questions regarding custody, or non-English-speaking parents. The non-participants did not differ from participants in sex, race, or neonatal characteristics. Although some children were in full-time special education programs (n = 16) or home schooled (n = 3), most attended regular education classrooms (n = 129). The control group consisted of 111 term-born NBW children (GA >36 weeks, birth weight > 2500 g) matched individually to EPT/ELBW children. NBW controls were from the same classrooms (n = 93) or other classrooms (n = 18) in the same or demographically similar schools as the EPT/ELBW children and were the closest matches on sex, race, and age at assessment. NBW controls were recruited only for the EPT/ELBW children attending regular classrooms and were not available for 18 of these children because of school refusals/inaccessibility or difficulty recruiting appropriate matches. All children were assessed during their first year in kindergarten, a year focused on development of learning readiness and beginning academic skills.

Children who were unable to complete achievement testing because of inattentiveness, lack of cooperation, or inability to understand basic test demands were excluded from this study, resulting in a final sample of 140 EPT/ELBW children and 110 NBW controls. Additional children were untestable on some of the cognitive tasks, further reducing sample size for the cognitive model to 121 EPT/ELBW children and 100 NBW controls. Table 1 summarizes group demographic and neonatal characteristics. The groups did not differ significantly in sex, race, age at assessment, or level of maternal education. The EPT/ELBW had higher rates of delayed school entry than the NBW group (21% vs. 3%, $p < 0.001$) but the groups did not differ in rates of preschool attendance (84% vs. 86%). Because each EPT/ELBW child had to be assessed before recruitment of the