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Basic Information Processing Abilities at 11 years Account for Deficits in IQ Associated with Preterm Birth

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Abstract

Although it is well established that preterms as a group do poorly relative to their full-term peers on tests of global cognitive functioning, the basis for this relative deficiency is less understood. The present paper examines preterm deficits in core cognitive abilities and determines their role in mediating preterm/full-term differences in IQ. The performance of 11-year-old children born preterm (birth weight <1750g) and their full-term controls were compared on a large battery of 15 tasks, covering four basic cognitive domains -- *memory, attention, speed of processing and representational competence*. The validity of these four domains was established using latent variables and confirmatory factor analysis (CFA). Preterms showed pervasive deficits within and across domains. Additionally, preterm deficits in IQ were completely mediated by these four cognitive domains in a structural equation model involving a cascade from elementary abilities (attention and speed), to more complex abilities (memory and representational competence), to IQ. The similarity of findings to those obtained with this cohort in infancy and toddlerhood suggest that preterm deficits persist – across time, across task, and from the non-verbal to the verbal period.

Children born prematurely are at risk not only for neurological and physical handicaps, but also for a broad spectrum of intellectual and behavioral problems, often termed 'high prevalence/low severity' impairments (Aylward, 2002). Although survival rates have increased over the past 20 years, rates of disability have remained fairly constant, with impairment being more pronounced with decreasing birthweight and gestational age. Compared to their full-term peers, preterms commonly have lower IQ (even when IQ is within the normal range) and poorer academic achievement, particularly in math (Aylward, 2002; Bhutta, Cleves, Casey, Cradock, & Anand, 2002). While the degree of relative deficit

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in IQ varies, a meta-analysis of 15 follow-up studies found the weighted mean difference between groups to be about 10 points (Bhutta et al., 2002).

One approach to understanding the basis for the IQ disparity between preterms and full-terms lies in examining differences between the groups in elementary cognitive abilities which may contribute, collectively, to their more general deficits. There is a long history of viewing basic abilities as important constituents of higher level cognitive outcomes. Adopting this ‘componential approach,’ Detterman (1987) was able to identify a small set of independent abilities which, when taken together, accounted for much of the variance in IQ, while DeFries and Plomin (1985) identified a set of four specific abilities that accounted for the variance in ‘g.’ Recent studies have pointed out the pivotal role played by elementary abilities in ‘executive functions’ (EF), a term referring to a diverse set of complex cognitive skills associated with cognitive flexibility, self-regulation, planning and problem solving. Salthouse (2005) and Nettlebeck & Burns (2010) have both endorsed models demonstrating developmental cascades in adults whereby age related declines in EFs are mediated by declines in more basic cognitive abilities. Processing speed and memory figure prominently in these models (for related work linking attention and EF, see Scope, Empson, & McHale, 2010).

In earlier work, we identified, in infancy, four core cognitive abilities that are distinguishable from each other, even within the first year of life -- attention, speed of processing, memory, and representational competence (Rose, Feldman, & Jankowski, 2004, 2005b). These core cognitive abilities proved to be sensitive to prematurity and instrumental in mediating preterm/full-term differences in general cognitive ability. Preterm deficits were found in these elementary abilities throughout the first years of life (Rose, Feldman, & Jankowski, 2001; 2002; 2003; 2005a); the same deficits were found again, when the children were 2 and 3 years of age, indicating that they persist at least through toddlerhood (Rose et al., 2009b). Moreover, these deficits have been shown to account for preterm/full-term differences in general cognitive ability, assessed with the Mental Developmental Index (MDI) from the Bayley scales at 2 and 3 years; this was true whether the information processing abilities were assessed at 7 months (Rose, Feldman, Jankowski, & Van Rossem, 2005) or at 12 months (Rose, Feldman, Jankowski, & Van Rossem, 2008).

Core Abilities

These four domains were initially targeted in our work because of research with normally developing populations suggesting that they are key to more complex cognitive functioning. *Memory* is considered vital for storing, consolidating and retrieving representations of objects and events. Deficits in this area will limit learning and the accrual of knowledge. Two frequently studied aspects of memory— recognition and recall – are dependent on the hippocampus and associated structures and were of particular interest since they are especially vulnerable to injury from the hypoxic/ischemic attacks to which preterms are prone (Volpe, 1995). Short-term capacity, an aspect of memory mediated by more frontal brain areas, was of interest because of its critical role in working memory, itself pivotal for many higher order abilities (Fry & Hale, 1996; Kyllonen & Christal, 1990).

Processing Speed was singled out because it is often considered the central limiting factor for performance on a wide variety of tasks. For example, increased processing is associated with improved mental rotation and memory search, increased working memory capacity, and enhanced inductive reasoning (Kail & Salthouse, 1994). Processing speed increases substantially in early childhood and continues to increase during late childhood and adolescence (Kail, 1991). Recent imaging studies have shown that processing speed is

largely dependent on cerebral white matter, and that white matter volume and concentration is greatly reduced among preterms (Giménez et al., 2006; Soria-Pastor et al., 2008).

Attention was included because it is vital for selecting and maintaining focus. Deficits in sustained attention, where focus on a continuous and repetitive task must be maintained over a prolonged period, are thought to reflect impulsivity (Taylor, Hack, & Klein, 1998). Deficits in selective attention, where a cognitive set must be maintained in the face of distracting or competing stimuli, may be due either to difficulties in attention shifting (engaging and/or disengaging fixations) or to a narrowness of the ‘attentional spotlight’ (the amount of information processed within each fixation; see Posner & Petersen, 1990).

Representational Competence, an umbrella term referring to the ability to extract commonalities from experiences and represent them symbolically, is critical for all types of abstract thought. One aspect of this ability we have assessed is tactual-visual cross-modal, where children have to abstract information about a form tactually, and then recognize the form when it was presented visually (Rose, Feldman, Futterweit, & Jankowski, 1998). Other aspects have been assessed by evaluating children’s ability to extract underlying rules and use them to anticipate future events, and evaluating their ability to mentally manipulate and rotate parts to form a whole.

Preterm Performance on Core Abilities

While deficits in some of these abilities have been found in preterm follow-up studies, most studies have focused on younger children – preschool and the early school ages (Breslau, Chilcoat, DelDotto, Andreski, & Brown, 1996; Korkman, Liikanen, & Fellman, 1996). Comparatively few studies have assessed more elementary abilities in children older than 9 years, and the results have been mixed. For example, in one study, where 15-year-olds were tested on a large battery that included both core abilities and EF tasks (digit span, verbal memory, figure copying, trail-making and verbal fluency), preterms showed deficits only on verbal fluency (Rushe et al., 2001). By contrast, using a similarly large and diverse battery, preterm deficits were found at 16 years on tasks assessing a number of basic abilities (Taylor, Minich, Bangert, Filipek, & Hack, 2004), including memory (pattern recognition, spatial span), processing speed (letter cancellation), visual-motor skill (copying and remembering designs), and spatial judgment (matching line orientation). In other studies, deficits have been reported at 11 years on some tasks of memory and processing speed, but not others (Rose & Feldman, 1995, 1997). Overall, it is not clear whether the deficits in basic abilities commonly found through the early school years persist (Elgen, Lundervold, & Sommerfelt, 2004; Luu et al., 2009; Rose, Feldman, Jankowski et al., 2005; Rose et al., 2008), increase (O’Brien, Roth, Rifkin, Rushe, & Wyatt, 2004), or abate (Rushe et al., 2001; Saavalainen et al., 2007). As Taylor noted (Taylor et al., 2004), to some extent the inconsistencies in findings may be attributed to inappropriate (or absent) control groups, cohort effects, or the use of a limited set of outcome measures. These inconsistencies may also be due to the tendency to use a single measure to operationalize a construct, a strategy which decreases the robustness of any findings.

Present Study

The present study has three principal aims: (1) to ascertain whether the deficits found in four key cognitive abilities in the infant and toddler years – attention, processing speed, memory, and representational competence – persist into adolescence; (2) to determine the role of these core abilities in mediating preterm/full-term differences in IQ; and (3) to determine whether a model of the role of these abilities found to fit data from infancy (both 7 and 12 months) in accounting for preterm/full-term differences in MDI at 2 and 3 years was applicable at this later age. In this model, the more elementary abilities (attention and speed)

influenced the more complex ones (memory and representational competence), which in turn influenced general cognitive ability in a cascade of influence that fully accounted for preterm/full-term differences in general cognition. Showing that this model holds in adolescence, with more traditional instantiations of the constructs, would support the idea that this model depicts fundamental relations among cognitive constructs that are age-invariant.

Methods

Participants

Participants were full-term and preterm infants who were enrolled in a prospective, longitudinal study of cognitive development. The original sample included 203 children (59 preterm infants and 144 term controls), born between February 1995 and July 1997. Preterm infants (defined as birth at < 37 weeks of gestation) were recruited from consecutive births admitted to the neonatal intensive care units of two hospitals affiliated with Albert Einstein College of Medicine. Criteria for study intake were: singleton birth, birthweight <1750 g, and the absence of any obvious congenital, physical, or neurological abnormalities. The medical risk factors of preterms who returned at 11 years are shown in Table 1; they are similar to those of the original cohort. (For further details see Rose, Feldman, & Jankowski, 2001). Although the vast majority of preterm (82%) were born at relatively low gestational age (< 32 weeks), the sample covered the full spectrum of preterm birth. Recent research shows that all preterms, even the 'late-preterm' (born at 34-36 weeks gestational age) show increased morbidity and mortality, along with increased cognitive problems during childhood (Engle, Tomashek, Wallman, & the committee on fetus and newborn, 2007; Talge et al., 2010).

Full-term infants were recruited from consecutive births from the same hospitals; criteria for study intake were birthweight >2500 g, gestational age of 38-42 weeks, 5-minute Apgar scores of 9 or 10, and uneventful pre- and perinatal circumstances. Previous follow-up visits were at 5, 7, 12, 24, and 36 months.

Attrition—Of the original 203 children, 134 returned at 11 years, for a follow-up rate of 74.9% for preterms ($N = 44$) and 62.5% for full-terms ($N = 90$). As is customary in this literature, data for children who developed any serious neurological condition since their last follow-up at age 3 were excluded from analysis ($N = 3$ full-terms), as was the data of one child that could not be retrieved in time for these analyses ($N = 1$ full-term), leaving an effective sample of 130 children (44 PT and 86 FT).

Background characteristics—Background characteristics of the preterms and full-terms seen at 11-years were similar to one another (and to the original cohort), in gender, birth order, ethnicity, parental education, and socio-economic status (SES), with 51.1% male, 33.6% first born, and 85.5 % either Black or Hispanic. Maternal education averaged 13.6 years ($SD = 2.1$) and SES, as assessed with the Hollingshead Four-Factor Index (Hollingshead, 1975), averaged 36.6 ($SD = 13.0$).

Procedure

The children were seen at 11 years for a full day of testing. In general, the morning session ran from approximately 9-12:30, with one 20-minute break; the afternoon session ran from 1:15 - 4, with one 20-minute break. Additional breaks were given if needed. The information processing tasks presented here, which are part of a larger battery, cover four cognitive domains (memory, processing speed, attention, and representational competence) and were chosen to be conceptually homologous to those used previously with this cohort, in infancy

and early childhood (Rose et al., 2009b; Rose, Feldman, Jankowski et al., 2005; Rose et al., 2008).

The tasks included computerized assessments, paper-and-pencil tasks, and experimental tasks. The computerized assessments were drawn largely from two well-standardized computer batteries of non-verbal tasks, where responses are recorded via a touch screen: the Cambridge Neuropsychological Testing Automated Battery (CANTAB; Cambridge Cognition, 2005) and the Cognitive Abilities Test (CAT; Detterman, 1988). The paper-and-pencil tasks came largely from a factor-analytically derived paper-and-pencil battery: the Specific Cognitive Abilities Tests (SCA; DeFries & Plomin, 1985). The reliabilities of these batteries is good, with internal consistency coefficients on the CANTAB tasks ranging from .73 to .95 for 4- to 12-year-olds (Luciana & Nelson, 2002), and internal consistency and split-half reliabilities on the CAT and SCA generally in the .80s or above (DeFries & Plomin, 1985; Detterman, 1988). Many of the tasks are graded in difficulty, thus minimizing floor and ceiling effects. The tasks in the present paper also included a paper-and-pencil measure of pattern span (Della Sala, Gray, Baddeley, & Wilson, 1997), a computerized version of span of apprehension (Bedwell, Esposito, & Miller, 2004), created with E-Prime, and an experimentally derived task of cross-modal transfer. The number of children completing any one task varied from 126-130; data loss on particular tasks was due to equipment failure, parental time constraints, or failure to complete the task.

Measures

Memory: Recognition

Pattern Recognition (CANTAB): This task assesses both immediate and delayed recognition. Initially, a series of 12 abstract patterns are presented sequentially, for 3 s each. The patterns then appear again, each now paired with a new one, and the child must identify which had been previously presented (immediate recognition). A second set of twelve patterns is presented next and recognition is tested after a 20 min delay (delayed recognition). Measures: Percent correct (immediate and delayed). Approximate time: 5 min.

Delayed Match-to-Sample (CANTAB): The child is shown a complex abstract stimulus and must select a match from four choices. Target and choices are either presented simultaneously or successively, with choices presented after variable delays of 0, 4, or 12 s. There are 10 counterbalanced trials in each condition, for a total of 40 trials. Measure: Number correct. Approximate time: 10 min.

Spatial Recognition (CANTAB): Five squares appear on the screen successively, each in a unique location. Subsequently, each is paired with a square in a new location and the child must indicate which one is in a previously occupied location. There are 3 blocks of 5 trials, for a total of 15 trials. Measure: Percent correct. Approximate time: 5 min.

Memory: Recall

Probe Recall (CAT): This task assesses immediate recall. On each trial, 6 patterns are presented sequentially, for 1 s each, one in each of six boxes arrayed horizontally on the screen. A probe pattern then appears, and the child must indicate its previous spatial location. There are 72 trials, 12 probing each of the six positions. Measure: Percent correct. Approximate time: 17 min.

Name-Face Association (SCA): This task assesses immediate and delayed recall. The child is shown a page of eight photographs of faces, each with its name printed below. The experimenter names each, in turn, and then the child has 1 min to study the page. With the

photos re-ordered (and names removed), recall is tested immediately and after a 20 min delay. Measures: Number correct (immediate and delayed). Approximate time: 5 min.

Memory: Short-term Capacity

Spatial Span (CANTAB): In this task, modeled after the Corsi block test, nine empty boxes are randomly arrayed on the screen. Initially, two light up, one at a time, and the child must reproduce the sequence by touching the appropriate boxes in the correct order. Sequences increase in length from 2 to 9. There are 3 trials at each level, and testing is discontinued when the child fails all three. Measure: Longest sequence correctly recalled (span length). Approximate time: 5 min.

Pattern Span (Visual Patterns Test: Della Sala et al., 1997): The child views a 2-dimensional grid composed of equal numbers of filled (black) and unfilled (white) squares for 3 s. An empty grid is then presented, and the child has to mark the filled squares from the studied pattern. Grids increase in complexity from 2 to 15 filled squares. Three attempts are allowed at each level and testing is discontinued when the child fails all three. Measure: Largest grid correctly reproduced (span length). Approximate time: 3-5 min.

Speed of Processing

Tachistoscopic Threshold (CAT): In this inspection time task (assessing encoding speed) two patterns are presented briefly and the child indicates whether they are the same or different. Trials begin with a 1/60 s exposure and, using the ascending method of limits, is incremented by 1/60 s after an error, and reduced by 1/60 s after a correct response. Trials continue until the child makes 5 consecutive correct responses. The presentation time for these 5 trials is the threshold for the block. There are 20 such blocks of trials. Measure: Median threshold (in msec) for the 20 blocks. Approximate time: 10-15 min

Reaction Time (CAT): This task evaluates simple and choice reaction time (RT). One, two, four, six, or eight windows are displayed on the screen in a semi-circular array and the child had to touch, as quickly as possible, the window that lights up. Variable delays are used (200, 300, 400 ms) and there are 24 trials at each set size (1, 2, 4, 6, 8). Sets are presented in ascending order, for a total of 120 trials. Measure: RT. Approximate time: 10-15 min.

Match-to-Sample (SCA): In this visual search task the child must find, from among 4 alternatives, the one matching a target. Targets and alternatives are sequences of letters and numbers that differ only in their ordering. One minute is given to complete as many items as possible. Measure: Number correct minus number incorrect. Approximate time: 1 min.

Attention

Rapid Visual Information Processing (CANTAB): This continuous performance (vigilance) task assesses sustained attention. The child monitors a stream of successively presented digits and indicates, on a press pad, when a particular sequence of three numbers (3-5-7) has appeared. Single digits, ranging from 2-9, appear in a pseudo-random order at the rate of 100/min. There are 300 trials, containing 24 target sequences. Measures: numbers of hits, misses, and correct rejections; probability of false alarms; signal detection index of sensitivity to the target. Approximate time: 7 min.

Span of Apprehension (computerized task adapted from (Bedwell et al., 2004): This task of selective attention assesses the accuracy with which a target can be apprehended when distracters are present. Each trial (50 msec) consists of 1, 6, or 12 randomly arrayed letters; the child indicates which target – a “T” or “F” – was present, by pressing one of two computer keys. There are six blocks of 10 trials, two for each array size; for a total of 60

trials. Blocks are presented in pseudo-random order. Measure: Number correct. Approximate time: 3 min.

Representational Competence

Tactual-Visual Cross-modal Transfer (adapted from James et al., 2002 and Rose & Feldman, 1995): In this task, information about shape must be extracted from one modality and applied to another. On each trial, the child palpates a 3-dimensional abstract shape for 15 sec and then must select the shape previously felt from four that are visually presented. Shapes were created from lego blocks and are presented affixed to a stationary base. (Individual shapes measured about 4" × 2" and all could be easily grasped.) There are 20 trials, 10 in which the orientation of the familiar stimulus is unchanged from familiarization to test and 10 in which it is rotated 180 degrees. Measure: Number correct. Approximate time: 15 min.

Spatial Relations (SCA): This task involved choosing which of four line drawings would, when rotated, complete a square that is missing a piece. The child is given four minutes to complete as many problems as possible (out of 20). Measure: Number correct. Approximate time: 4 min.

Hidden Patterns (SCA): In this task the child has to circle all the line drawings on a page that contain hidden within them the target figure pictured at the top. The child is given 3 minutes to complete as many problems as possible. Measure: Number correct minus incorrect. Approximate time: 3 min.

Intelligence

Wechsler Intelligence Scale for Children-III (WISC-III): This test was used to assess general intellectual functioning.

Results

Preterm/full-term Differences

Univariate and bivariate distributions were initially examined for all variables, separately by group, and outlying values (> 2.5 SD from the mean or regression line) were winsorized. Preterm/full-term differences were assessed using ANOVA, with birth status (preterm = 0 vs. full-term = 1) as the grouping factor. Repeated measures ANOVAs (with Type III sums of squares) were used for tasks having multiple measures (e.g., immediate and delayed tests) or multiple levels (e.g., number of choices in the RT task). Effect sizes (η^2) are provided for all tests. All analyses were repeated controlling for gender, and with children having IQ < 70 removed ($n = 5$ preterms); none of the group differences were affected.

Memory

Recognition: Preterms showed poorer performance than full-terms on all three recognition tasks, significantly so on two of them: *Delayed Match-to-Sample*, $F(1, 125) = 6.47, p < .05, \eta^2 = .05$, *Spatial Recognition*, $F(1, 127) = 7.18, p < .01, \eta^2 = .05$, and *Pattern Recognition*, $F(1, 127) = 3.22, p < .10, \eta^2 = .02$. As expected, on the two tasks that varied the retention interval, performance deteriorated systematically with increasing delays: *Delayed Match-to-Sample*, $F(3, 375) = 65.39, p < .001, \eta^2 = .05$, and *Pattern Recognition*, $F(1, 127) = 224.84, p < .001, \eta^2 = .64$. On the latter task, which included a relatively lengthy delay of 20 minutes, there was also a significant birth status $\times$ delay interaction, $F(1, 127) = 3.96, p < .05, \eta^2 = .03$, with performance showing an even greater fall-off for preterms than full-terms.

Recall: Preterms showed significantly poorer performance than full-terms on *Probed Recall*, $F(1,127) = 7.81, p < .01, \eta^2 = .06$ and marginally poorer performance on *Name- Face Association*, $F(1, 124) = 2.96, p < .10, \eta^2 = .02$. On *Name- Face Association*, where the retention interval was varied, there was also a significant effect for delay, $F(1,124) = 39.31, p < .001, \eta^2 = .24$, indicating that recall was poorer with longer retention intervals.

Short-term capacity: Preterms were not able to keep as many items in mind at one time as were full-terms over a short period, as indicated by poorer performance on both memory span tasks: *Visual Span*, $F(1,126) = 18.35, p < .001, \eta^2 = .13$, and *Spatial Span*, $F(1,127) = 7.04, p < .01, \eta^2 = .05$.

Speed—Preterms were slower at processing information than full-terms, significantly so on all three tasks. Preterms needed about 40% longer exposure than full-terms to determine whether two briefly presented stimuli were the same or different on the task assessing *Tachistoscopic Threshold* task, $F(1,128) = 14.11, p < .001, \eta^2 = .10$, found fewer matches than full-terms in the allotted time on *Match-to-Sample*, $F(1,127) = 4.64, p < .05, \eta^2 = .04$, and took around 50 ms longer, on average, to respond to the appearance of a target in the task assessing *Reaction Time*, $F(1,128) = 3.50, p < .10, \eta^2 = .03$. On *Reaction Time*, response times increased systematically for both groups as the number of choices increased from one to eight, $F(4,512) = 23.84, p < .001, \eta^2 = .16$.

Attention—Preterms had poorer selective attention: *Span of Apprehension*, $F(1,124) = 4.43, p < .05, \eta^2 = .04$. Performance worsened as the number of distracters increased, $F(2,246) = 182.23, p < .001$, an effect that was more pronounced in preterms than full-terms, as evidenced by a significant interaction between birth status and the number of distracters, $F(2,246) = 3.66, p < .05, \eta^2 = .03$. Thus, while the ability to detect the presence of a target (“T” or “F”) fell-off for both groups as the number of distracters increased, the fall-off was greater for preterms.

Preterms also had poorer sustained attention, as indicated by several measures from *Rapid Visual Processing*: sensitivity to the target (the A' measure), $F(1,126) = 3.22, p < .10, \eta^2 = .02$; correct rejections, $F(1,127) = 3.81, p = .05, \eta^2 = .03$; false alarms, $F(1,127) = 4.11, p < .05, \eta^2 = .03$. Thus, preterms showed lower sensitivity to the target, had fewer correct rejections, and more false alarms than full-terms. There were no significant group differences in either the number of hits or the number of misses.

Preterms also had poorer sustained attention, as indicated by several measures from *Rapid Visual Processing*. Relative to full-terms, preterms had fewer correct rejections, $F(1,127) = 3.81, p = .05, \eta^2 = .03$, more false alarms, $F(1,127) = 4.11, p < .05, \eta^2 = .03$, and lower sensitivity to the target (the A' measure), $F(1,126) = 3.22, p < .10, \eta^2 = .02$. There were no significant group differences in either the number of hits or the number of misses.

Representational Competence—Preterms showed poorer performance on all three tasks assessing representational competence: *Tactual-Visual Cross-Modal Transfer*, $F(1,125) = 11.03, p = .001, \eta^2 = .08$; *Hidden Figures*, $F(1,126) = 5.60, p < .05, \eta^2 = .04$; and *Spatial Relations*, $F(1,126) = 7.86, p < .01, \eta^2 = .06$. They made more errors selecting the correct visual match to the object they had been feeling, whether the test stimuli were presented in the same orientation on familiarization and test, or rotated 180°, found fewer hidden patterns in the allotted time, and made more errors when they had to mentally rotate alternatives to find the piece which would successfully complete a square.

Intelligence—Preterms also had lower IQs than full-terms, with a significant difference of almost 10 points on the WISC-III full-scale IQ, $F(1,129) = 17.55, p < .001, \eta^2 = .12$.

Relation of Medical risk to Information Processing in Preterms—For the most part, there were only sporadic relations between the medical risk factors for preterms, shown in Table 1, and measures of information processing. The principal exception was the memory composite representing short-term capacity, which was related to a number of the preterm medical risk factors, including 1-min Apgar ($r = .31$), 5-min Apgar ($r = .44$), the presence of RDS ($r = -.30$), and two indices of RDS severity, namely, days on oxygen ($r = -.36$) and days on CPAP ($r = -.38$), all $ps < .05$.

Confirmatory Factor Analysis

Confirmatory factor analysis (CFA) was performed with LISREL (Ver 8.54: Jöreskog & Sörbom, 2003) using maximum likelihood estimation, with missing data (1.3% of all values) imputed using the Expected Maximization (EM) algorithm in PRELIS. The statistical goodness of fit for each model was assessed using the normal theory weighted least squares χ^2 , the root mean square error of approximation (RMSEA), the comparative fit index (CFI), and the non-normed fit index (NNFI). Values indicative of good fit are a non-significant χ^2 at $p = .05$, a RMSEA $< .05$ (though an RMSEA $< .10$ is considered acceptable (Browne & Cudeck, 1993), and a CFI and NNFI $> .90$.

Memory was indexed by the mean accuracy scores on the three tasks of recognition, the two tasks of recall, and the two tasks of short-term capacity. Processing speed was indexed by median threshold on Tachistoscopic Threshold and mean latency to respond on Reaction Time. Representational Competence was indexed by accuracy scores on Cross-Modal Transfer, Hidden Figures, and Spatial Relations. Because in a 4-factor model the two attention variables loaded very low on the common factor, a 5-factor model was estimated with two single-indicator attention factors: Sustained Attention (indexed by the accuracy scores on Span of Apprehension) and Selective Attention (indexed by total correct rejections of Rapid Visual Processing). Following Huizinga et al (Huizinga, Dolan, & van der Molen, 2006), we refer to this model, which incorporates both latent and manifest variables, as a “partial measurement model.” The visual pattern task was dropped from the CFA because it had a somewhat different pattern of relations with other measures than the rest of the memory variables.

Correlations among the information processing measures are shown in Table 3, along with their relation to prematurity and IQ. The results of the CFA are shown in Table 4: the top portion provides the factor loading of each task on its latent variable, whereas the bottom portion provides the correlations among factors. Fit statistics for this model indicate that it provided an excellent fit to the data, $\chi^2 (69) = 85.80$, $p = .08$, $\chi^2/df = 1.24$, RMSEA = .04, CFI = .97, NNFI = .96. The standardized factor loadings for multiple indicator latent variables ranged from .41 to .73, all significant at $p < .01$.¹

We examined alternative models by combining one or more latent factors (setting relations between them in ψ to 1) and removing one or more correlations among latent factors (fixing their intercorrelations in ψ to 0), then testing whether the constrained models provided a significantly better fit to the data (as indicated by significant χ^2 difference tests). The results indicated that none of the alternative models fit significantly better than the original. Combined, these findings support the partial measurement model in Table 3, where the three latent factors representing Memory, Processing Speed, and Representational Competence are each separable from one another and from the two manifest variables representing different aspects of Attention.

¹Because tachistoscopic threshold had cross-loading of .47 on the Memory Factor that was higher than the loadings of the delayed-match-to sample name-face recall on that variable, the CFA was re-run removing these two measures from the model. The fit was not appreciably affected, with the new model having $\chi^2(46) = 62.28$, $p = .06$, $\chi^2/df = 1.35$, RMSEA = .052, CFI = .97, NNFI = .96.

We next examined whether the basic measurement model in Table 4 was invariant across preterms and full-terms using a 2-group version of this model, which sequentially introduced constraints on factor loadings, latent variables (correlations and variances), and the error variances of observed variables. With only factor loadings constrained to be equal across groups, a good fit was achieved: $\chi^2(148) = 169.96$, $p = .11$, $\chi^2/df = 1.15$, RMSEA = .048, CFI = .94, NNFI = .93. The fit remained good even with additional constraints imposed on the equality of covariances among latent factors: $\chi^2(160) = 188.91$, $p = .06$, $\chi^2/df = 1.18$, RMSEA = .053, CFI = .94, NNFI = .93.2 Moreover, these additional constraints did not result in a significant decrease in fit, $\Delta\chi^2(12) = 18.95$, $p > .05$. While the fit remained adequate when equality constraints were additionally imposed on the error variances, $\chi^2(172) = 248.07$, $p < .001$, $\chi^2/df = 1.44$, RMSEA = .083, CFI = .90, NNFI = .89, this model did not fit as well as the previous one, $\Delta\chi^2(12) = 59.16$, $p < 0.001$. Overall, these findings indicate that the basic measurement model fit well for both groups.

Mediators of Preterm/Full-term Differences in IQ

To test the hypothesis that information processing would mediate the relation of birth status to IQ, a structural model was specified in which the information processing measures influenced one another in a cascading fashion. This model replicates, at age 11, the cascade models used earlier to demonstrate the ability of homologous information processing factors in infancy to completely mediate the relation between birth status and MDI at ages 2 and 3 (Rose et al., 2005, 2008). In the current model, the two elementary infant information processing abilities – attention and speed—influenced the two more complex infant abilities – recognition and representational competence – which, in turn, influenced IQ. Thus, the model included paths from (a) birth status to the four cognitive abilities and IQ, (b) the more elementary abilities to the more complex ones, and (c) the more complex information processing abilities to IQ.

Birth status was coded 1 for children born at term and 0 for those born prematurely. Latent factors not causally related were allowed to correlate. Correlations between error terms in the measurement model (see footnote 2) were also allowed here, as was that between the error terms of IQ and one of the speed tasks (match-to-sample, which is methodologically similar to the two speed tasks that contribute to IQ).

The results are depicted in Fig 1. The model provided a good fit to the data, $\chi^2(87) = 89.92$, $p = .394$, $\chi^2/df = 1.03$, RMSEA = .016, CFI = .99, NNFI = .99, CAIC = 377.43, accounting for 58% of the total variance in IQ. The standardized estimates are shown in Fig 1, along with their significance level.³

Three points are noteworthy. First, the relation of birth status to IQ was entirely mediated by the information processing measures. The direct path was non-significant, standardized $\beta = .06$ ($t = .84$, ns). In fact, more than 90% of the total effect of birth status on IQ (.36, $p < .01$) was indirect (.30, $p < .01$). Thus, the lower scores of preterms on IQ at 11 years can be attributed largely to poorer information processing.

Second, the two more complex abilities, memory and representational competence, were both directly related to MDI. The standardized direct effects for each of these constructs $\beta = .38$ ($t = 2.90$, $p < .01$), and $\beta = .44$ ($t = 3.57$, $p < .01$), respectively.

²In this two-group CFA model, correlations were allowed in full-terms between the error variances for spatial span and two related CANTAB measures, spatial recognition and delayed-match-to-sample.

³Because the construct of attention was not as well represented as we would have liked, the mediation model was re-run removing the two single-indicator attention latent factors. The results were substantially unchanged, $\chi^2(69) = 90.10$, $p = .05$, $\chi^2/df = 1.31$, RMSEA = .05, CFI = .97, NNFI = .96, model CAIC = 301.32, with the same paths significant as in the original and the path from birth status to IQ reduced to non-significance.

Third, of the two more elementary infant abilities, only speed was indirectly related to IQ, going through both memory and representational competence. The standardized indirect effect for speed on IQ was .65 ($t = 2.93$, $p < .01$).⁴

An alternative model was tested that contained no cascade, but only direct paths from all four information processing measures to IQ, as well as the same correlations between error terms allowed in the original model. This model did not fit the data as well, $\chi^2(90) = 125.95$, $p < .01$, RMSEA = .056, CFI = .96 and NNFI = .94; the model CAIC = 395.86. Moreover, the cascade model fit significantly better than this one, as indicated by the lower CAIC and a significant chi-square difference between the two, $\Delta \chi^2(3) = 36.03$, $p < .001$.

Ancillary Analyses—These analyses were run to determine whether the four elementary cognitive abilities were predictive of full-scale IQ in the two groups separately, and whether they predicted over and above medical risk for the preterms. This was done using factor scores created from the latent variables in the CFA, and entering them into a multiple regression. For full-terms, the four information processing measures accounted for more than half the variance in IQ, $R^2 = .51$, $F(5, 79) = 16.47$, $p < .001$; for preterms, they accounted for close to 40% of the variance, $R^2 = .39$, $F(5, 33) = 4.23$, $p < .005$. A medical risk index was created for the preterms to determine whether information processing predicted IQ over and above risk status. The risk index was created, using principal component analysis, from the factors listed in Table 1 (excluding 1 min Apgar and NMI, which were redundant with other measures). This risk factor correlated .32 ($p < .05$) with preterm IQ.⁵ The first principal component, which accounted for 50% of the variance of these measures, was used as the index of risk. In a hierarchical regression, the 5 information processing measures were entered in a second step, following the risk index. These measures accounted for 33% of the variance in IQ over and above that accounted for by medical risk, a highly significant increase, $F(5, 79) = 16.47$, $p < .001$.

Discussion

This study assessed information processing in a cohort of 11-year-old preterms and full-terms, group-matched on SES and gender. Children were tested on a large battery covering four major cognitive domains: memory, attention, speed of processing and representational competence. There were three major findings. First, deficits in preterms relative to their full-term peers were evident at 11 years, just as they had been in infancy, in all four cognitive domains. Second, these deficits were pervasive and together, fully accounted for preterm deficits in full-scale IQ. Third, a model describing the route by which these preterm deficits account for more global ones fit the data well at this age, just as it had in infancy. This model incorporated a cognitive cascade whereby more elementary cognitive abilities influenced more complex ones.

This study is one of the few to examine preterm performance in early adolescence on core information processing abilities and the first to show that these key abilities underlie preterm deficits in IQ. These findings parallel those obtained in infancy and toddlerhood, where preterms showed deficits in the same domains, suggesting that deficits in these abilities, which have their roots in infancy, persist. In the current study, as in infancy, these deficits fully accounted for the preterm/full-term difference in measures of more global cognitive

⁴To determine whether the effect of speed was, in fact, only indirect, the mediation model was re-run, including a direct path from speed to IQ. This path was not significant (standardized $\beta = .04$, $p = .30$), while the paths from memory and representational competence to IQ were little changed ($\beta = .35$ and $\beta = .42$, respectively, both $p < .01$). The model fit was substantially the same as the original: $\chi^2(86) = 89.80$, $p = .37$, $\chi^2/df = 1.04$, RMSEA = .019, CFI = .99, NNFI = .99, model CAIC = 383.18.

⁵Of the nine individual components, the following five correlated significantly ($r = .33$ to $.43$, $p < .05$) with IQ: birthweight, 5-min Apgar, days on respirator, days on oxygen, and length of hospitalization.

functioning, indexed in infancy by Bayley MDI scores at 2 and 3 years (Rose, Feldman, Jankowski et al., 2005; Rose et al., 2008), and here by the WISC-III full-scale IQ. Taken together, these results are consistent with the notion that specific, elementary cognitive abilities are the building blocks of global cognitive measures.

Pervasive Preterm Deficits

Memory deficits were found for preterms in assessments of in recognition, recall, and short-term capacity. Although several studies have examined preterm memorial abilities, with mixed results, many of these studies have used verbal measures (Dewey, Crawford, Creighton, & Suave, 1999; Taylor et al., 2004). In the present study, the memory tasks were either entirely or largely non-verbal, thus avoiding or minimizing any confound between memory and verbal ability. The three types of memory investigated here were singled out for examination because they are thought to depend on different brain substrates (Quamme, Yonelinas, Widaman, Kroll, & Suave, 2004; Rose, Feldman, Jankowski, & Van Rossem, 2011; Yonelinas, Otten, Shaw, & Rugg, 2005). Although studies examining memory deficits in adolescent preterms using non-verbal tasks are sparse, a few have employed some of the same tasks used here (namely Cantab spatial span, Cantab pattern recognition, and SCA name-face association) and obtained similar results (Curtis, Lindeke, Georgieff, & Nelson, 2002; Luciana & Nelson, 2002; Rose & Feldman, 1996; Taylor et al., 2004). Preterm deficits in recognition and recall are actually not unexpected, given that both depend on the hippocampus (de Haan, Mishkin, Baldeweg, & Vargha-Khadem, 2006; DeBoer, Wewerka, Bauer, Georgieff, & Nelson, 2005), and given that the hippocampus is uniquely sensitive to the types of hypoxic/ischemic episodes to which preterms are prone (Volpe, 2008). In fact, reductions in hippocampal volume have been found in preterm adolescents and linked to memory deficits in both recognition (Gimenez et al., 2004) and recall (Isaacs et al., 2000).

Processing speed was slower among preterms on tasks of encoding speed (tachistoscopic threshold), reaction time, and search time (match-to-sample). Although processing speed is often considered key to many other types of cognitive functions (Kail, 1991; Kail & Salthouse, 1994; Rose, Feldman, & Jankowski, 2003; Salthouse, 1996), it has rarely been studied in preterms. In the one study that did examine this issue in some detail, 11-year-old preterms were slower than their full-term controls on the same three tasks used here (Rose & Feldman, 1996, 1997). There is growing evidence of an association between processing speed and white matter integrity (Kennedy & Raz, 2009) as well as an association between premature birth and compromised white matter integrity. Modern imaging studies have found reductions among preterms in white matter concentration and volume using voxel-based morphometry (Giménez et al., 2006) and widespread fiber tract disorganization, using diffusion tensor imaging and fractional anisotropy (Constable et al., 2008). Moreover, a direct association was recently found in preterm adolescents between compromised white matter integrity and measures of processing speed (Soria-Pastor, 2008).

Attention was also poorer in preterms, who showed deficits in both sustained and selective attention. Although many studies have found preterm birth to be associated with increased risk for ADHD in adolescence (Aarnoudse-Moens, Weisglas-Kuperus, & van Goudoever, 2009; Bhutta et al., 2002), very few have directly assessed attention in adolescence. The few studies of sustained attention that have used the Connors' Continuous Performance Test have not found preterm deficits in adolescents (Elgen et al., 2004; Grunau, Whitfield, & Fay, 2004; Kulseng et al., 2006), although deficits have been found with a similar task from the CANTAB, namely, Rapid Visual Information Processing (Taylor et al., 2004), which was used in the present study. The contrasting results may be due to the difference in task structure: whereas the Connors' task requires responding on most trials (and not responding to the target), the CANTAB task requires just the opposite, namely, withholding a response on most trials (and responding to the target). The increased requirement for inhibition of

responding on the CANTAB may account for its greater success in discriminating between groups. The deficits found in the present study for selective attention are consonant with those from studies using other measures of this ability (Taylor, Klein, & Minich, 2000; Taylor et al., 2004). Recently it has been suggested that sustained attention is dependent on the microstructure of the superior longitudinal fasciculi, white matter tracts that are abnormal in preterms (Frye, Hasan, Malmberg, Desouza, & Swank, in press).

Representational competence was assessed here with two visuo-spatial tasks and a task of tactual-visual cross-modal transfer that included trials requiring mental rotation of the tactually presented forms before visually identifying them. In this domain too, preterms did worse than their controls. Preterms' poor performance on these tasks is in accord with the widespread findings of visuo-spatial deficits and with previous findings from our earlier cohort (Rose & Feldman, 1995). Deficits in visuo-spatial tasks are likely to be associated with damage to some of the same parietal areas involved in IQ (Grefkes, Weiss, Zilles, & Fink, 2002).

Specific abilities mediate preterm/fullterm differences in IQ

While it is well established that preterm deficits in global cognitive function are present in adolescence (Botting, Powls, Cooke, & Marlow, 1998; Breslau, Paneth, & Lucia, 2004; Saigal, Hoult, & Streiner, 2000; Taylor et al., 2004), there have been few attempts to account for these deficits in terms of discrete neuropsychological functions. The present study is among the first to address this issue. Preterm/full-term differences in IQ were completely accounted for in a model involving a cascade of effects: prematurity → elementary cognitive processes (speed and attention) → complex processes (memory and representational competence) → IQ. The findings suggest that preterms' shortcomings in basic aspects of information processing underlie preterm/full-term differences in IQ.

Conclusion

These results, together with previous findings from our lab (Rose & Feldman, 1997), make a strong case for the critical role of basic abilities in preterm outcome. In the earlier studies, preterm deficits in measures from these same domains were detected as early as 5 months, and were found to persist over at least the first three years of life (Rose et al., 2001; Rose, Feldman, & Jankowski, 2002; Rose et al., 2003, 2004; Rose, Feldman, & Jankowski, 2005a; Rose, Feldman et al., 2005b; Rose et al., 2009b). Information processing measures from the infancy period mediated the relation between prematurity and (a) Bayley Scores at 2 and 3 years (Rose et al., 2009b; Rose, Feldman, Jankowski et al., 2005; Rose et al., 2008), and (b) language proficiency at these same ages (Rose et al., 2009b). The present study showed that deficits in these same domains were present at age 11, as the children enter adolescence, and that these deficits mediated preterm/full-term differences in IQ. By looking at the same core cognitive domains at multiple ages, a strategy that is rare in preterm studies, we were able to document the persistence of deficits from infancy to adolescence.

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References

- Aarnoudse-Moens CS, Weisglas-Kuperus N, van Goudoever JB. Meta-analysis of neurobehavioral outcomes in very preterm and/or very low birth weight children. *Pediatrics*. 2009; 124:717–728. [PubMed: 19651588]

- Aylward GP. Cognitive and neuropsychological outcomes: More than IQ scores. *Mental Retardation and Developmental Disabilities Research Reviews*. 2002; 8:234–240. [PubMed: 12454899]
- Bedwell JS, Esposito S, Miller LS. Accelerated age-related decline of visual information processing in first-degree relatives of persons with schizophrenia. *Psychiatry Research*. 2004; 125:225–235. [PubMed: 15051183]
- Bhutta AT, Cleves MA, Casey PH, Cradock MM, Anand KJS. Cognitive and behavioral outcomes of school-aged children who were born preterm: A meta-analysis. *Journal of the American Medical Association*. 2002; 288:728–736. [PubMed: 12169077]
- Botting N, Powls A, Cooke RWI, Marlow N. Cognitive and educational outcome of very-low-birthweight children in early adolescence. *Developmental Medicine and Child Neurology*. 1998; 40:652–660. [PubMed: 9851233]
- Breslau N, Chilcoat H, DelDotto JE, Andreski P, Brown GG. Low birth weight and neurocognitive status at six years of age. *Biological Psychiatry*. 1996; 40:389–397. [PubMed: 8874840]
- Breslau N, Paneth NS, Lucia VC. The lingering academic deficits of low birth weight children. *Pediatrics*. 2004; 114:1035–1040. [PubMed: 15466102]
- Browne, MW.; Cudeck, R. Alternative ways of assessing model fit. In: Bollen, KA.; Long, JS., editors. *Testing structural equation models*. Sage; Beverly Hills, CA: 1993. p. 136–162.
- Constable RT, Ment LR, Vohr BR, Kesler SR, Fulbright RK, Lacadie C, Delancy S, Katz KH, Schneider KC, Schafer RJ, Makuch RW, Reiss AL. Prematurely born children demonstrate white matter microstructural differences at 12 years of age, relative to term control subjects: An investigation of group and gender effects. *Pediatrics*. 2008; 121:306–316. [PubMed: 18245422]
- Curtis WJ, Lindeke L, Georgieff MK, Nelson CA. Neurobehavioural functioning in neonatal intensive care unit graduates in late childhood and early adolescence. *Brain*. 2002; 125:1646–1659. [PubMed: 12077013]
- de Haan M, Mishkin M, Baldeweg T, Vargha-Khadem F. Human memory development and its dysfunction after early hippocampal injury. *Trends in Neurosciences*. 2006; 29:374–261. [PubMed: 16750273]
- DeBoer T, Wewerka S, Bauer PJ, Georgieff MK, Nelson CA. Explicit memory performance in infants of diabetic mothers at 1 year of age. *Developmental Medicine and Child Neurology*. 2005; 47:525–531. [PubMed: 16108452]
- DeFries, JC.; Plomin, R. *Origins of individual differences in infancy: The Colorado Adoption Project*. Academic Press; Orlando, Florida: 1985.
- Della Sala, S.; Gray, C.; Baddeley, A.; Wilson, L. *Visual patterns test: A test of short-term visual recall*. Thames Valley Test Company; Bury St Edmunds: 1997.
- Detterman DK. Theoretical notions of intelligence and mental retardation. *American Journal of Mental Deficiency*. 1987; 92:2–11. [PubMed: 3618654]
- Detterman, DK. CAT: Cognitive Abilities Test (unpublished test). Cleveland, Ohio: 1988. Unpublished manuscript
- Dewey D, Crawford SG, Creighton DE, Suave RS. Long-term neuropsychological outcomes in very low birthweight children free of sensorineural impairments. *Journal of Clinical and Experimental Neuropsychology*. 1999; (21):851–865. [PubMed: 10649539]
- Elgen I, Lundervold AJ, Sommerfelt K. Aspects of inattention in low birth weight children. *Pediatric Neurology*. 2004; 30:92–98. [PubMed: 14984899]
- Engle WA, Tomashek KM, Wallman C, the Committee on Fetus and Newborn. “Late-preterm” infants: A population at risk. *Pediatrics*. 2007; 120:1390–1401. [PubMed: 18055691]
- Fry AF, Hale S. Processing speed, working memory, and fluid intelligence: Evidence for a developmental cascade. *Psychological Science*. 1996; 7:237–241.
- Frye RE, Hasan K, Malmberg B, Desouza L, Swank P. Superior longitudinal fasciculus and cognitive dysfunction in adolescents born preterm and at term. *Developmental Medicine and Child Neurology*. (in press).
- Giménez M, Junqué C, Narberhaus A, Bargalló N, Botet F, Mercader JM. White matter volume and concentration reductions in adolescents with history of very preterm birth: A voxel-based morphometry study. *NeuroImage*. 2006; 32(4):1485–1498. [PubMed: 16809052]

- Gimenez M, Junque C, Narberhaus A, Caldu X, Salgado-Pineda P, Bargallo N, Segarra D, Botet F. Hippocampal gray matter reduction associates with memory deficits in adolescents with history of prematurity. *NeuroImage*. 2004; 23:869–877. [PubMed: 15528087]
- Grefkes C, Weiss PH, Zilles K, Fink GR. Crossmodal processing of object features in human anterior intraparietal cortex: An fMRI study implies equivalencies between human and monkeys. *Neuron*. 2002; 35:173–184. [PubMed: 12123617]
- Grunau RE, Whitfield ME, Fay TB. Psychosocial and academic characteristics of extremely low birthweight (< or = 800 g) adolescents who are free of major impairment compared with term-born control subjects. *Pediatrics*. 2004; 114:e725–732. [PubMed: 15576337]
- Huizinga M, Dolan CV, van der Molen MW. Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia*. 2006; 44:2017–2036. [PubMed: 16527316]
- Isaacs EB, Lucas A, Chong WK, Wood SJ, Johnson CL, Marshall C, Vargha-Khadem F, Gadian DG. Hippocampal volume and everyday memory in children of very low birth weight. *Pediatric Research*. 2000; 47:713–720. [PubMed: 10832727]
- James TW, Humphrey GK, Gati JS, Servos P, Menon RS, Goodale MA. Haptic study of three-dimensional objects activates extra-striate visual areas. *Neuropsychologia*. 2002; 40:1706–1714. [PubMed: 11992658]
- Jöreskog, K.; Sörbom, D. LISREL. Version 8.54. Scientific Software International, Inc.; 2003.
- Kail R. Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin*. 1991; 109:490–501. [PubMed: 2062981]
- Kail R, Salthouse TA. Processing speed as a mental capacity. *Acta Psychologica*. 1994; 86:199–225. [PubMed: 7976467]
- Kennedy KM, Raz N. Aging white matter and cognition: Differential effects of regional variations in diffusion properties on memory, executive functions, and speed. *Neuropsychologia*. 2009; 47:916–927. [PubMed: 19166865]
- Korkman M, Liikanen A, Fellman V. Neuropsychological consequences of very low birthweight and asphyxia at term: follow-up until school-age. *Journal of Clinical and Experimental Neuropsychology*. 1996; 18:220–233. [PubMed: 8780957]
- Kulseng S, Jennekens-Schinkel A, Naess P, Romundstad P, Indredavik M, Vik T, Brubakk A-M. Very-low-birthweight and term small-for-gestational-age adolescents: Attention revisited. *Acta Paediatrica*. 2006; 95(2):224–230. [PubMed: 16449031]
- Kyllonen PC, Christal RE. Reasoning ability is (little more than) working-memory capacity?! *Intelligence*. 1990; 14:389–433.
- Luciana M, Nelson CA. Assessment of neuropsychological function through use of the Cambridge Neuropsychological Testing Automated Battery: Performance in 4- to 12-year-old children. *Developmental Neuropsychology*. 2002; 22(3):595–624. [PubMed: 12661972]
- Luu TM, Ment LR, Schneider KC, Katz KH, Allan WC, Vohr BR. Lasting effects of preterm birth and neonatal brain hemorrhage at 12 years of age. *Pediatrics*. 2009; 123:1037–1044. [PubMed: 19255037]
- Nettlebeck T, Burns NR. Processing speed, working memory and reasoning ability from childhood to old age. *Personality and Individual Differences*. 2010; 48:379–384.
- O'Brien F, Roth S, Rifkin L, Rushe T, Wyatt J. The neurodevelopmental progress of infants less than 33 weeks into adolescence. *Archives of Disease in Childhood*. 2004; (89):207–211. [PubMed: 14977690]
- Posner MI, Petersen S. The attention system of the human brain. *Annual Review of Neuroscience*. 1990; 13:25–42.
- Preacher KJ, Hayes AW. Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behavior Research Methods*. 2008; 40(3):879–891. [PubMed: 18697684]
- Quamme JR, Yonelinas AP, Widaman KF, Kroll NEA, Suave MJ. Recall and recognition in mild hypoxia: using covariance structural modeling to test competing theories of explicit theories. *Neuropsychologia*. 2004; 42:672–691. [PubMed: 14725804]

- Rose SA, Feldman JF. Prediction of IQ and specific cognitive abilities at 11 years from infancy measures. *Developmental Psychology*. 1995; 31:685–696.
- Rose SA, Feldman JF. Memory and processing speed in preterm children at 11 years: A comparison with full-terms. *Child Development*. 1996; 67:2005–2021. [PubMed: 9022226]
- Rose SA, Feldman JF. Memory and speed: Their role in the relation of infant information processing to later IQ. *Child Development*. 1997; 68:630–641. [PubMed: 9306643]
- Rose SA, Feldman JF, Futterweit LR, Jankowski JJ. Continuity in tactual-visual cross-modal transfer: Infancy to 11 years. *Developmental Psychology*. 1998; 34:435–440. [PubMed: 9597354]
- Rose SA, Feldman JF, Jankowski JJ. Attention and recognition memory in the first year of life: A longitudinal study of preterms and full-terms. *Developmental Psychology*. 2001; 37:135–151. [PubMed: 11206428]
- Rose SA, Feldman JF, Jankowski JJ. Processing speed in the 1st year of life: A longitudinal study of preterm and full-term infants. *Developmental Psychology*. 2002; 38(6):895–902. [PubMed: 12428702]
- Rose SA, Feldman JF, Jankowski JJ. Infant visual recognition memory: Independent contributions of speed and attention. *Developmental Psychology*. 2003; 39(3):563–571. [PubMed: 12760523]
- Rose SA, Feldman JF, Jankowski JJ. Dimensions of cognition in infancy. *Intelligence*. 2004; 32:245–262.
- Rose SA, Feldman JF, Jankowski JJ. Recall memory in the first three years of life: A longitudinal study of preterms and full-terms. *Developmental Medicine and Child Neurology*. 2005a; 47:653–659. [PubMed: 16174307]
- Rose SA, Feldman JF, Jankowski JJ. The structure of infant cognition at 1 year. *Intelligence*. 2005b; 33:231–250.
- Rose SA, Feldman JF, Jankowski JJ. A cognitive approach to the development of early language. *Child Development*. 2009a; 80:134–150. [PubMed: 19236397]
- Rose SA, Feldman JF, Jankowski JJ. Information processing in toddlers: Continuity from infancy and persistence of preterm deficits. *Intelligence*. 2009b; 37:311–320. [PubMed: 20161244]
- Rose SA, Feldman JF, Jankowski JJ, Van Rossem R. Pathways from prematurity and infant abilities to later cognition. *Child Development*. 2005; 76:1172–1184. [PubMed: 16274433]
- Rose SA, Feldman JF, Jankowski JJ, Van Rossem R. A cognitive cascade in infancy: Pathways from prematurity to later mental development. *Intelligence*. 2008; 36:367–378. [PubMed: 19122757]
- Rose SA, Feldman JF, Jankowski JJ, Van Rossem R. The structure of memory in infants and toddlers: An SEM study with full-terms and preterms. *Psychological Science*. 2011; 14:83–91.
- Rushe TM, Rifkin L, Stewart AL, Townsend JP, Roth SC, Wyatt JS, Murray RM. Neuropsychological outcome at adolescence of very preterm birth and its relation to brain structure. *Developmental Medicine and Child Neurology*. 2001; 43:226–233. [PubMed: 11305398]
- Saavalainen P, Luoma L, Bowler D, Maatta S, Kiviniemi V, Laukkanen E, Herrgard E. Spatial span in very prematurely born adolescents. *Developmental Neuropsychology*. 2007; 32:769–785. [PubMed: 17956181]
- Saigal S, Hoult LA, Streiner DL. School difficulties in adolescence in a regional cohort of children who were extremely low birth weight. *Pediatrics*. 2000; 105:325–331. [PubMed: 10654950]
- Salthouse TA. The processing-speed theory of adult age differences in cognition. *Psychological Review*. 1996; 103:403–428. [PubMed: 8759042]
- Salthouse TA. Relations between cognitive abilities and measures of executive functioning. *Neuropsychology*. 2005; 19:532–545. [PubMed: 16060828]
- Scope A, Empson J, McHale S. Executive function in children with high and low attentional skills: Correspondences between behavioural and cognitive profiles. *British Journal of Developmental Psychology*. 2010; 28:293–305. [PubMed: 20481389]
- Soria-Pastor S, Gimenez M, Narberhaus A, Falcon C, Botet F, Bargallo N, Mercader JM, Junque C. Patterns of cerebral white matter damage and cognitive impairment in adolescents born very preterm. *International Journal for Developmental Neuroscience*. 2008; 26:647–654.

- Talge NM, Holzman C, Wang J, Lucia V, Gardiner J, Breslau N. Late-preterm birth and its association with cognitive and socioemotional outcomes at 6 years of age. *Pediatrics*. 2010; 126:1124–1131. [PubMed: 21098151]
- Taylor HG, Hack M, Klein NK. Attention deficits in children with <750 gm birth weight. *Child Neuropsychology*. 1998; 4(1):21–34.
- Taylor HG, Klein N, Minich NM. Middle-school-age outcomes in children with very low birthweight. *Child Development*. 2000; 71:1495–1511. [PubMed: 11194251]
- Taylor HG, Minich N, Bangert B, Filipek PA, Hack MB. Long-term neuropsychological outcomes of very low birth weight: Associations with early risks for periventricular brain insults. *Journal of the International Neuropsychological Society*. 2004; 10:987–1004. [PubMed: 15803562]
- Volpe, JJ. *Neurology of the Newborn*. third edition. W.B. Saunders; Philadelphia, Pennsylvania: 1995.
- Volpe, JJ. *Neurology of the Newborn*. 5th ed. Elsevier; Philadelphia: 2008.
- Yonelinas AP, Otten LJ, Shaw KN, Rugg MD. Separating the brain regions involved in recollection and familiarity in recognition memory. *Journal of Neuroscience*. 2005; 25(11):3002–3008. [PubMed: 15772360]

Figure 1.

The pathways from prematurity and infant information processing at 11 years to full-scale IQ. Significant paths are indicated by solid lines; insignificant paths by broken lines. Parameter estimates are shown for the completely standardized solution. [†] $p < .06$, * $p < .05$, ** $p < .01$.

Table 1

Medical characteristics of the preterms (N = 44)

	Mean	SD	Range	%
Birthweight (g)	1165.2	268.4	751–1747	
LBW (1500 g–1750g)				11.4
VLBW (1000g – 1499 g)				59.1
ELBW (<1000 g)				29.5
Gestational age at birth (weeks)	29.7	2.8	25–36	
34–36 weeks				9.1
32–33 weeks				9.1
<32 weeks				81.8
Apgar				
1 Minute	5.7	2.5	1–9	
5 Minute	7.5	1.5	4–9	
Time on Respirator (days)	6.1	8.0	0–31	
Time on Oxygen (days)	18.9	21.3	0–82	
Time in Hospital (days)	49.9	22.5	7–106	
Neonatal Medical Index (NMI) ^a	3.6	1.4	1–5	
Small for Gestational Age (SGA) ^b				27.3
Respiratory Distress Syndrome (RDS)				50.0
Ultrasound Diagnosis				
No Abnormality				56.8
Germinal Matrix / Intraventricular Hemorrhage				43.2
Parenchymal lesion / Ventricular enlargement				0.0

^aHigher scores indicate more severe complications.^bDefined as having a birth weight below 10% of the population for a given gestational age.

Table 2

Preterm/Full-Term Differences

Domains / Measures	Preterm (N = 44)		Full-term (N = 86)		Significant F-tests
	M	SD	M	SD	
MEMORY					
Recognition					
Pattern Recognition (CANTAB) – % correct					Birth Status [†] Delay ^{***} Interaction [*]
Immediate	91.67	9.79	92.73	9.11	
20 min delay	70.16	17.37	74.22	15.50	
Delayed Match-to-Sample (CANTAB) – % correct					
Simultaneous (control)	94.53	10.96	96.30	8.32	Birth Status [*] Delay ^{***}
0 s delay (Immediate)	72.56	22.69	79.76	18.17	
4 s delay	67.21	24.04	74.76	19.72	
12 s delay	62.17	25.31	67.61	21.03	
Spatial Recognition (CANTAB) – % correct	75.58	10.48	80.75	10.28	Birth Status ^{**}
Recall					
Probe recall (CAT) – % correct	38.98	6.25	42.25	6.2	Birth Status [*]
Name-Face Association (SCA) – # correct					
Immediate	4.14	1.79	4.64	1.90	Birth Status [†] Delay ^{***}
Delayed (20 min)	3.28	2.19	3.99	2.02	
Short Term Capacity					
Visual (VPT) – span length	5.91	1.62	7.31	1.81	Birth Status ^{***}
Spatial (CANTAB) – span length	5.33	1.21	5.90	1.15	Birth Status ^{**}
PROCESSING SPEED					
Tachistoscopic Threshold (CAT) - Median (ms)	167.07	79.94	121.57	56.22	Birth Status ^{***}

Domains / Measures	Preterm (N = 44)		Full-term (N = 86)		Significant F-tests
	M	SD	M	SD	
Reaction Time (CAT) - Mean decision time (ms)					
1 choice	527.65	118.24	503.85	102.10	Birth Status [†] ***
2 choices	564.00	131.95	537.59	107.75	
4 choices	600.09	162.47	556.21	115.97	
6 choices	602.81	168.99	553.63	113.79	
Match-to-Sample (SCA) – # correct	11.21	4.03	12.76	3.75	Birth Status [*]
ATTENTION					
Span of Apprehension – % correct					
1 letter (0 distractors)	89.51	11.77	89.68	10.23	Birth Status [*] *** Interaction [*]
6 letters (5 distractors)	65.85	15.85	73.75	15.82	
12 letters (11 distractors)	61.95	11.72	65.71	12.99	
Rapid Visual Processing (CANTAB)					
Sensitivity to target – A'	.94	.05	.96	.04	Birth Status [†]
Number of Hits	19.47	3.41	20.26	3.03	Birth Status [*] ***
Number of Misses	4.53	3.41	3.97	3.72	
Number of Correct Rejections	259.63	15.80	264.02	9.70	
Probability of False Alarms	.02	.04	.01	.02	Birth Status [*]
REPRESENTATIONAL COMPETENCE					
Tactual-Visual Cross-Modal Transfer – # correct					
Without rotation	4.57	1.64	5.12	1.62	Birth Status ^{***}
With rotation	4.14	1.76	5.27	1.72	
Hidden Figures (SCA) – # correct	19.79	10.58	24.45	10.49	Birth Status [*]
Spatial Relations (SCA) – # correct	8.28	7.05	11.49	5.61	Birth Status ^{**}
INTELLIGENCE					
WISC-III					
	85.68	14.26	95.44	11.62	Birth Status ^{***}

† $P < .10$,
 * $P < .05$,
 ** $P < .01$,
 *** $P < .001$

Table 3

Correlations among Measures

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(1) Preterm / Full-term Status															
(2) Pattern Recognition – % correct	.16														
(3) Delayed Match-to-Sample – % correct	.20	.22													
(4) Spatial Recognition – % correct	.20	.31	.28												
(5) Probe recall – % correct	.23	.36	.37	.34											
(6) Name-Face recall – # correct	.13	.26	.17	.28	.27										
(7) Spatial span – span length	.23	.20	.09	.42	.34	.19									
(8) Tachistoscopic Threshold - Median (ms) ^I	.32	.29	.30	.22	.36	.16	.26								
(9) Reaction Time - Mean decision time (ms) ^I	.16	.18	.29	.21	.34	.19	.22	.45							
(10) Search speed on match-to-sample – # correct	.19	.19	.16	.00	.22	.22	.21	.34	.25						
(11) Span of Apprehension – % correct	.14	.23	.18	.13	.22	.21	.16	.43	.32	.33					
(12) Rapid Visual Processing – total correct rejections	.17	.24	.27	.09	.21	.17	.27	.31	.45	.42	.21				
(13) Tactual-Visual Cross-Modal Transfer – # correct	.28	.26	.10	.29	.36	.20	.38	.35	.26	.29	.18	.26			
(14) Hidden Figures – # correct	.20	.29	.19	.18	.36	.23	.22	.32	.20	.40	.30	.36	.36		
(15) Spatial Relations – # correct	.22	.29	.06	.17	.25	.14	.30	.23	.19	.17	.18	.24	.37	.52	
(16) WISC Full-Scale IQ	.34	.29	.34	.29	.43	.22	.43	.41	.32	.57	.29	.40	.39	.55	.48

Note. N = 123 – 129. Correlations with an absolute value > .17 are significant at $p < .05$; those with an absolute value > .22 are significant at $p < .01$.

^I Score is reversed; all measures are scaled so that high scores indicate good performance.

Table 4

Confirmatory Factor Analysis of Core Neuropsychological Abilities

	Latent Factors			
	Memory	Processing Speed	Sustained Attention	Selective Attention Representational Competence
<i>Factor Loadings</i>				
Pattern Recognition – % correct	.54**			
Delayed Match-to-Sample – % correct	.42**			
Spatial Recognition – % correct	.53**			
Probe recall – % correct	.69**			
Name-Face recall – # correct	.42**			
Spatial span – span length	.52**			
Tachistoscopic Threshold - Median (ms) ¹		.65**		
Reaction Time - Mean decision time (ms) ¹		.60**		
Search speed on match-to-sample – # correct		.56**		
Span of Apprehension – % correct			1.00**	
Rapid Visual Processing -- total correct rejections				1.00**
Tactual-Visual Cross-Modal Transfer -- # correct				.58**
Hidden Figures – # correct				.73**
Spatial Relations – # correct				.63**
<i>Interfactor Correlations</i>				
Memory	— — — —			
Processing Speed	.73**	— — — —		
Sustained Attention	.60**	.34**	— — — —	
Selective Attention	.63**	.38**	.21*	— — — —
Representational competence	.69**	.67**	.45*	.34**

¹ Score is reversed; all measures are scaled so that high scores indicate good performance.

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