Published in final edited form as:

Intelligence. 2012 ; 40(5): 445–457. doi:10.1016/j.intell.2012.05.007.

Information Processing from Infancy to 11 Years: Continuities and Prediction of IQ

Susan A. Rose^{a,*}, Judith F. Feldman^a, Jeffery J. Jankowski^{b,a}, and Ronan Van Rossem^c

^aDepartment of Pediatrics, Albert Einstein College of Medicine/Children's Hospital at Montefiore, United States

^bDepartment of Social Sciences, Queensborough Community College/CUNY, United States

^cDepartment of Sociology, Ghent University, Belgium

Abstract

This study provides the first direct evidence of cognitive continuity for multiple specific information processing abilities from infancy and toddlerhood to pre-adolescence, and provides support for the view that infant abilities form the basis of later childhood abilities. Data from a large sample of children ($N = 131$) were obtained at five different time points (7, 12, 24, 36 months, and 11 years) for a large battery of tasks representing four cognitive domains (attention, processing speed, memory, and representational competence). Structural equation models of continuity were assessed for each domain, in which it was assumed that *infant abilities* $\rightarrow$ *toddler abilities* $\rightarrow$ *11-year abilities*. Abilities at each age were represented by latent variables, which minimize task-specific variance and measurement error. The model for each domain fit the data. Moreover, abilities from the three age periods predicted global outcome, with infant, toddler, and contemporaneous 11-year measures, respectively, accounting for 12.3%, 18.5%, and 45.2% of the variance in 11-year IQ. These findings strengthen contentions that specific cognitive abilities that can be identified in infancy show long-term continuity and contribute importantly to later cognitive competence.

Keywords

Infancy; Toddlerhood; Pre-adolescence; Cognitive continuity; Information Processing; IQ

The remarkable surge of research on infant cognition over the last 40 years or so has revealed a wide range of competencies present in the first year or two of life. Our present understanding of the infant mind belies Garrett's view of early cognition as an amorphous general ability that only gradually breaks down into more distinct abilities (Garrett, 1946), and puts to rest William James' earlier characterizations of the infant mind as a "blooming, buzzing confusion." Today we recognize that infants exhibit a number of basic cognitive skills. They are able to distribute attention across competing stimuli, recognize and recall events, readily encode information, and abstract statistical regularities from the perceptual

© 2012 Elsevier Inc. All rights reserved.

*Corresponding author: Susan A. Rose, Departments of Pediatrics, Kennedy Center, Albert Einstein College of Medicine/Children's Hospital at Montefiore, 1300 Morris Park Avenue, Bronx, NY 10461. Tel: 718-430-3042. Fax: 718-430-8544. susan.rose@einstein.yu.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

flux. Evidence from factor analytic studies supports the existence of discrete domain-specific abilities in the first year of life (Rose, Feldman, & Jankowski, 2004a; Rose, Feldman, & Jankowski, 2005b).

Nonetheless, questions remain about the relation of infant abilities to later cognition. One question concerns the extent to which specific infant abilities are qualitatively similar to their later counterparts. At the heart of this issue is the extent to which specific infant abilities show continuity over the course of development. A second question concerns the extent to which infant abilities form the building blocks of the more global aspects of later cognitive ability. These issues are addressed in the present study by examining longitudinal relations from infancy and toddlerhood to 11 years within four domains – attention, processing speed, memory, and representational competence – and the relation of infant and toddler abilities from these domains to 11 year IQ.

Background

Disparity in task demands

The issue of cognitive continuity from infancy to later years is bedeviled by two problems. First, it has long been thought that the cognitive processes in infancy were fundamentally different from those characterizing mature cognition. And indeed, there is empirical data showing that scores obtained during the first year of life on traditional infant tests, such as the Bayley Scales of Infant Development, do not predict later cognition (Bayley, 1949). Second, even for specific abilities that do exist in infancy, the disparities in task demands across the ages might obscure any underlying continuities. Very different methods, task content, and instructions are used to assess cognition in infants and in older children. For example, infant measures are totally non-verbal and rely principally on preferential looking, look duration, and imitation; ‘instructions’ per se are non-existent, and knowledge of competence is inferred from the behaviors observed. By contrast, at older ages, tasks utilize precise instructions that directly indicate what is expected, and responses typically have a verbal component, factors which help to disambiguate task requirements and encourage the formulation and implementation of strategic approaches, such as grouping, rehearsal, or refreshing.

Visual recognition memory provides a typical example of the age-related disparities that exist between infant and adult tasks designed to assess the same ability. In infancy, visual recognition memory is generally assessed with the paired-comparison paradigm, where a target is presented for familiarization and then the familiar target and a new one are paired on test; recognition is inferred from preferential looking to the new target (Fagan, 1970; Rose, Feldman, & Jankowski, 2004b). It is assumed, following Sokolov (1963), that the infant creates a mental representation during familiarization; when a new target is encountered on test that does not match a stored representation, attention shifts to the new target so that information about that target may be assimilated. (Thus, preference for a new stimulus can be taken as evidence for a stored representation of the old one.) In adolescence and adulthood, on the other hand, visual recognition memory is generally assessed by having subjects store multiple targets in memory and then indicate the one previously seen when it is presented along with a foil in a forced-choice task. Attention is another process that is measured quite differently in infancy and older children. In infancy, this ability is often inferred from look durations, or the number of shifts in gaze between targets, whereas in older children and adults, attention is often assessed with continuous performance tasks, where the subject monitors a repetitive stream of stimuli for infrequent targets (sustained attention), or with tasks where the subject must identify targets presented along with a number of distracters (selective attention).

Sparse literature

While there have been a number of studies relating infant attention and memory to later global indices of cognition, with infant measures predicting IQ even as much as 18 and 21 years later (Fagan, Holland, & Wheeler, 2007; Sigman, Cohen, & Beckwith, 1997; for a review see Fagan, 2011), only a handful have examined continuities in *specific* information processes or followed children beyond the preschool or early school years. Continuity of attention was found in one study, where preterm neonates who displayed relatively short fixations to a checkerboard pattern (indicative of efficient processing) showed better selective attention at 12 years (Sigman, Cohen, Beckwith, Asarnow, & Parmelee, 1991). While the sample was restricted to preterms, and the findings were not consistent across measures, the results are encouraging. Continuity in processing speed was found in another study, where measures of ocular RT from Haith's visual expectation paradigm at 3.5 months were found to correlate significantly with ocular RT at 4.5 years (although not with manual RT). While the sample was small ($N = 23$) and the follow-up period limited, here too the results are encouraging, particularly considering the centrality of processing speed to individual differences in other aspects of cognition (Anderson, 2001). And finally, continuities in memory have been found, with infant novelty scores from the paired-comparison task relating to more standard assessments of memory at 3, 6 and 11 years (Bauer, 2006; Fagan, 2011a; Rose & Feldman, 1997; Rose, Feldman, & Wallace, 1992; Thompson, Detterman, & Plomin, 1991). While the sample sizes were somewhat larger in these memory studies, only two cohorts were involved. In general, studies of infant-adolescent continuities are not only rare, but constructs tend to be operationalized by a single measure, and statistical procedures that minimize error variance, such as structural equation modeling (SEM) have not been used.

Present Study

The present study examines the presence of cognitive continuities and their relation to pre-adolescent IQ using data from a longitudinal cohort of children who were seen twice in infancy (7 and 12 months), twice in the toddler years (24 and 36 months), and then again at 11 years. The same measures, in the same formats, were used at the infant and toddler years to assess performance in four domains – processing speed, attention, memory, and representational competence. At 11 years, performance in these same four domains was assessed again, but here the tasks were those typically used with adolescents and adults.

The study had two principal aims: (1) to ascertain whether there are domain-specific cognitive continuities from the infant and toddler years to pre-adolescence, and (2) to determine the extent to which infant and toddler information processing abilities relate to 11 year IQ. Showing that infant and toddler abilities relate to the more traditional instantiations of these constructs would support the idea that later abilities have their roots in infancy.

Methods

Participants

Participants were full-term and preterm children 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. Preterms 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 for preterms were: singleton birth, birthweight < 1750 g, gestational age < 37 weeks, and the absence of any obvious congenital, physical, or neurological abnormalities. 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. Follow-up visits were at 5, 7, 12, 24, and 36 months, and 11 years. The present report, concerned with cognitive continuities, utilizes the infant and toddler data from 7 months onward of those who returned for the 11-year follow-up. (As discussed below, under Data Analysis, because relations among measures, including those between early and later measures, did not differ across groups, their data were combined for the analyses reported here.)

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 ($N=90$). Reasons for loss to follow-up from the inception of the study included (1) families now living out-of-state (5 preterms, 22 full-terms); (2) inability to locate families that had moved (8 preterms, 27 full-terms), and refusal to participate (2 preterms, 5 full-terms). Of the 134 children who returned for the 11-year follow-up, data for three children (full-terms) were excluded from consideration because they had who developed serious neurological disorders since their last follow-up, leaving an 11-year sample of 131 children (44 PT and 87 FT).

Background and medical characteristics—Background characteristics for the preterms and full-terms returning at 11-years were similar for the two groups (and similar to those of the original cohort; Rose, Feldman, & Jankowski, 2001). Overall, 51.1% of the sample were 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 ($SD=13.0$). The medical risk factors of preterms returning at 11 years were also similar to those of the original cohort. (For further details, see Rose et al., 2001).

Procedure: Infant and Toddler Period (7, 12, 24, and 36 months)

The measures from each of the four domains (memory, processing speed, representational competence, and attention) are listed in Table 1. The grouping in domains was based on theory and previous research, and confirmed by factor analysis (Rose et al., 2004a; Rose, Feldman, & Jankowski, 2005b).

The battery of tasks was given over two visits, with the second visit at each age scheduled two weeks after the first. (In rare cases, a third visit was required). Tasks were given in a standard format. To maximize interest, variations in stimuli and setting were introduced; thus some tasks were given in a three-sided booth and others at a table; some used photographs as stimuli and others used small three-dimensional objects or computer-generated images. Although the same measures, in the same format, were used throughout at all four ages, the tasks were modified to be age-appropriate, to avoid floor and ceiling effects, and to maximize inter-individual variability. Modifications included shortening presentation and test times, increasing the stringency of learning criteria, and in some instances, increasing stimulus complexity. Changes were based on extensive piloting.

Memory (Recognition and Recall)

Immediate Recognition—Infants' ability to recognize faces and colorful patterns were assessed using a 9-problem battery developed in our lab (Rose et al., 2001) and a 10-problem battery developed by Fagan (Fagan & Shepherd, 1989). In these problems, infants were familiarized with a stimulus and then tested for recognition by pairing the familiar with a novel target. In the Rose battery, five problems used black-and-white photographs of faces as targets and 4 used colorful abstract patterns. The problems were tailored to age by shortening familiarization and test times as age increased (from 20s and 5s at 7 months, for Faces and Patterns, respectively, to 5s and 3s at 36 months; test times also decreased over this period, from 10s to 4s). Recognition memory is typically inferred from differential

attention to the two test stimuli and is measured by the *novelty score* (the percentage of looking time devoted to the novel target). *Measure*: Mean novelty score.

Delayed Recognition—In this task, infants were habituated to three objects successively (using a modified infant-controlled procedure; see Diamond, 1990), and then, after a delay, given a series of test trials in which each habituation object was paired with a new one. This habituation-test procedure was repeated three times, with delays of 1, 3, and 5 min intervening between habituation and test, making nine problems in all. Habituation was infant-controlled, with objects presented until the infant had a few looks away (three 3s looks away or a minimum of 10s of accumulated looking at 7 months, to two 1s looks away, or a minimum of 2s of accumulated looking at 36 months). Novelty scores were calculated for each problem and averaged over all 9 problems (Rose et al., 2004a). *Measure*: Mean novelty score.

Recall Memory—Infant recall was evaluated using elicited imitation (Bauer, 2002). Here the child watches the experimenter model three or four event sequences, one at a time. (Sample 3-step sequence for ‘make a rattle’: place a small block on a paddle, cover it, and then shake the paddle to create a rattle sound). After a 15-min delay, the child is given the props for each event sequence, in turn, and encouraged to reproduce the sequences. This task was used beginning at 12 months. There were three sequences at 12 and 24 months, four at 36 months, with the number of actions/sequence varying from 3–4 at 12 months to 5–12 at 36 months; all actions had to be performed in a set order to achieve the outcome (‘enabling’) at the two younger ages; a few actions that could be performed in any order (‘arbitrary’) were introduced into two of the sequences at 36 months (Rose, Feldman, & Jankowski, 2005a). *Measures*: Mean percent target actions reproduced in the correct order.

Processing Speed

Psychomotor Speed (RT), the time to orient to a stimulus, was assessed with Haith’s Visual Expectation Paradigm (VExP; Haith, Hazan, & Goodman, 1988). Targets appear briefly on a computer screen to the L and R of midline, and the latency to look to each is measured (target durations dropped from 750 to 500 ms as age increased from 7–36 months; interstimulus intervals remained at 720 ms throughout). There were 10 baseline trials, where targets appeared randomly, followed by 60 predictable trials, where targets appeared in a right-right-left (RRL) sequence. A 150 ms cut-point separated anticipatory from reactive saccades; responses that occurred 150 ms after stimulus onset were scored as reaction times (Rose, Feldman, Jankowski, & Caro, 2002).

Measure: Mean RT

Encoding Speed—This aspect of speed was assessed with the ‘continuous familiarization’ task, in which infants were presented with a series of paired photographs of faces, one of which changed from trial to trial while the other remained constant (Fantz, 1961). Trials were shortened as age increased (from 4s to 1.5s as age increased from 7 to 36 months); testing continued until infants reached a criterion for having a consistent preference for the new one, defined as a run of 4 out of 5 consecutive trials having a novelty score > 55%, but < 100% at 7 months (which increased to a run of 6 out of 7 trials at 36 months), or until 36 trials had been presented (Rose, Feldman, & Jankowski, 2002). *Measure*: number of trials to criterion.

Representational Competence

Tactual-Visual Cross-Modal Transfer—This task, which assesses the ability to glean information about commonalities from experiences and represent them abstractly, required

extracting information about shape by feeling an object and then recognizing it visually. In this task, comprised of 11 problems, 3-dimensional geometric forms were presented tactually for familiarization, and then, on test, the previously felt object and a new one were presented visually. Familiarization times were shortened as age increased (from 40s to 15s; with test times dropping from 20s to 10s); novelty scores were used to index tactual-visual transfer (Rose, Feldman, Wallace, & McCarton, 1991). *Measure*: Mean novelty score.

Anticipations—The ability to anticipate forthcoming events was measured by the VExP task described above. Saccades to the up-coming stimulus were considered to be anticipatory if they were initiated before the stimulus could be perceived, i.e., prior to, or within 150 ms of, onset (the minimal time thought to be required to initiate a saccade; Haith et al., 1988). To successfully anticipate stimulus onset the child had to abstract the R-R-L rule governing changes in location for the fast-paced sequence of pictures. *Measure*: number of series trials with RTs < 150 ms.¹

Attention

Look duration, a measure of attentional efficiency (with short looks associated with better attention) was assessed using measures culled from a number of different tasks: familiarization and test phases of both tasks of visual recognition memory (the ‘Rose’ and the ‘Fagan’), the test phase of cross-modal transfer, and trials from the continuous familiarization task. Scores on each task were standardized and then averaged (Rose et al., 2004a; Rose, Feldman, & Jankowski, 2005b). *Measure*: composite representing average of the six standardized look duration scores.

Shift Rate, a measure capturing both attentional efficiency and comparison behavior, was assessed by calculating the number of shifts between stimuli per second (higher shift rates indicating better attention). These measures were available from all but one (the ‘Fagan’) of the tasks used for look duration; scores on each task were standardized and then averaged (Rose et al., 2004a; Rose, Feldman, & Jankowski, 2005b). *Measure*: composite, representing average of the five standardized shift rate scores.

Procedure: Pre-adolescent Period (11 years)

Information processing measures included in the 11-year follow-up (shown in Table 1) were designed to cover the same four cognitive domains (memory, processing speed, attention, and representational competence) and were chosen to be conceptually homologous to those used in the infant and toddler years (Rose, Feldman, & Jankowski, 2009; Rose, Feldman, Jankowski, & Van Rossem, 2005b, 2008a). The grouping of measures into these domains was supported by confirmatory factor analysis (Rose et al., 2011).

They included computerized assessments drawn largely from two well-standardized batteries, the Cambridge Neuropsychological Testing Automated Battery (CANTAB; Cambridge Cognition, 2005) and the Cognitive Abilities Test (CAT; Detterman, 1988), both of which used a touch screen to record responses, as well as paper-and-pencil tasks, drawn largely from a factor-analytically derived battery, the Specific Cognitive Abilities test (SCA; DeFries & Plomin, 1985). Also included was 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 reliabilities of tasks from the CANTAB and CAT are good, with internal consistency coefficients on the CANTAB tasks

¹Anticipations are not considered further because they did not correlate with cross-modal transfer at any age, did not form a latent factor, and did not relate to measures of later cognition.

ranging from .73 to .95 for 4- to 12-year-olds (Luciana & Nelson, 2002) and internal consistency coefficients and split-half reliabilities on the CAT and SCA generally .80 and above (DeFries & Plomin, 1985; Detterman, 1988). Many of the tasks are graded in difficulty, thus minimizing floor and ceiling effects. The number of children completing any one task varied from 126–131; data loss on particular tasks was due to equipment failure, parental time constraints, or failure to complete the task.

Memory: Recognition and Recall

Pattern Recognition (CANTAB)

This task assesses immediate and delayed recognition. Initially, a series of 12 abstract patterns are presented sequentially for 3s each. The patterns then reappear, 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 task-filled 20 min delay (delayed recognition). *Measure*: percent correct (averaged over immediate and delayed).

Delayed Match-to-Sample (CANTAB)

The child is shown a complex abstract stimulus and must select a match from four choices. With the exception of control trials, where the target and choices are presented simultaneously, targets and choices are presented successively, with choices presented after variable delays of 0, 4, or 12 s (10 trials in each condition, counterbalanced over the 40 trials). *Measure*: number correct (averaged over all delays).

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.

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. After a probe pattern appears, the child must indicate its previous spatial location. There are 72 trials, 12 probing each of the six positions. *Measure*: percent correct

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 task-filled 20 min delay. *Measures*: number correct (averaged over immediate and delayed).

Processing Speed

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. Each pattern is made up of 4×4 matrix of squares, some of which are filled, creating a simple geometric form. Trials begin with a 1/60 s exposure, and are then immediately covered by a solid mask. Using the ascending method of limits, exposure time 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 ms) for the 20 blocks.

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 must 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.

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 incorrect.

Representational Competence

Tactual-Visual Cross-Modal Transfer (adapted from James et al., 2002)

In this task, information about shape must be extracted from one modality and applied in another. On each trial, the child palpates a 3-dimensional abstract shape for 15 sec and then must select the shape previously felt (but not seen) from four that are visually presented. Shapes were created from lego blocks and are presented affixed to a stationary base. There are 20 trials, 10 with the familiar stimulus positioned the same on familiarization and test, and 10 with it rotated 180 degrees. Trials were interspersed in a pseudo-random order. Measure: Number correct.

Spatial Relations (SCA)

This task consists of a series of trials in which a square, missing a segment, is shown on the left, and four line drawings on the right. The child selects the line drawing that would, when rotated, complete the square. Four minutes are given to complete as many problems as possible (out of 20). Measure: Number correct.

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.

Attention

Rapid Visual Information Processing (CANTAB)

This continuous performance (vigilance) task assesses sustained attention. The child monitors a stream of 300 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 a total of 24 target sequences. Measures used here: number of false alarms; number of hits.

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 (averaged over array size).

Intelligence

Wechsler Intelligence Scale for Children (WISC-III)

This test was administered in its entirety and used to assess general intellectual functioning.

Data Analytic Plan

Preliminary analyses first examined all univariate and bivariate distributions for all variables; outlying values (> 2.5 SD from the mean or regression line) were winsorized. Where necessary (e.g., for reaction times), measures were rescaled to make higher scores indicate better performance. Because the sample involved preterm and full-term groups, all relations among measures were initially examined separately by group. Given that number of relations differing across groups did not exceed chance, data from the two groups were combined (and correlations partialled for birth status to avoid inflation due to group mean differences).

Structural Models of Continuity

Continuity across the three age periods – infancy, toddlerhood, and 11 years – was assessed using separate models for each of the four information-processing domains. For each model, three latent variables were assumed, one for each age period, with information processing at earlier ages predicting information processing at later ages. Thus, the influence from infancy to preadolescence was indirect, via toddlerhood. Alternative models having one additional path, a direct path from infancy to 11-years, were tested for each domain. These alternatives were compared to the original using the chi-square difference test.

Continuity models were fit using LISREL (Ver 8.54: (Jöreskog & Sörbom, 2003) using maximum likelihood estimation, with missing data (6.9% of all values) imputed using the Expected Maximization (EM) algorithm in PRELIS. Model fit was assessed using the normal theory weighted least squares χ^2 , the root mean square error of approximation (RMSEA), and the comparative fit index (CFI). Values considered indicative of good fit are a non-significant χ^2 , a RMSEA $< .08$ (Browne & Cudeck, 1993), and a CFI $> .90$.

A two-group model was also tested for each domain to determine whether continuities were influenced by birth status (preterm vs full-term). In these models, equality constraints were introduced across groups on factor loadings, variances and covariances among latent variables, and path coefficients.

Lisrel was also used to create factor scores from the latent variables of the continuity models. These were used to compare within-domain to cross-domain relations and as single indicators in regression models predicting 11-year IQ.

Results

Preliminary Analyses

Descriptive statistics for the measures are shown in Tables 1 and 2, and correlations among the information processing measures in each domain are shown in Table 3. Correlations are presented combined across preterms and full-terms because fewer than 5% of the correlations differed significantly between groups; they are partialled for prematurity to avoid their being inflated by any mean differences between groups.

The results in Table 3 show that, within each domain, measures tended to correlate modestly both within and across age; as would be expected, correlations tended to be greater across adjacent ages. The same trend was also true of associations of information processing with 11-year IQ.

Continuity in Attention

In this domain, the latent variables for infancy (7 and 12 months) and toddlerhood (2 and 3 years) were indexed by measures representing look duration and shift rate, while the 11-year latent variable was indexed by three measures — span of apprehension, and false alarms and hit rate from the Cantab Rapid Visual Processing task (Fig.1). The model fit the data adequately, with $\chi^2(12) = 17.95$, $p = .12$, RMSEA = .06, CFI = .97. All factor loadings were positive and significant, with standardized factor loadings ranging from .36 to .97 ($p < .01$). Paths from infancy to toddlerhood ($\beta = .42$) and from toddlerhood to attention at 11 years ($\beta = .28$) were both significant ($p < .01$), as was the indirect path from infant attention to 11-year attention, .12 ($p < .05$). In an alternative model, a direct path was added from infancy to 11-years. This direct path was not significant, and the alternative did not differ from the original, $\Delta \chi^2(2) = 0.48$.

Continuity in Processing Speed

In this domain, the infancy and toddler latent variables were indexed by measures representing reaction time from the Haith task, while the 11-year latent variable was indexed by three measures – reaction time, tachistoscopic threshold, and percent correct from the match-to-sample task (visual search). This model, shown in Fig 2, fits the data well, with $\chi^2(12) = 13.30$, $p = .35$, RMSEA = .03, CFI = .99. Again, all loadings were positive and significant, with standardized factor loadings ranging from .39 to .82 ($p < .01$). Paths from infancy to toddlerhood ($\beta = .75$) and toddlerhood to 11 years ($\beta = .39$) were both significant ($p < .01$), with an indirect effect of infant processing speed on 11-year processing speed of .29 ($p < .05$). Again, the alternative model, which added a direct path from infancy to 11-year speed, did not differ from the original, $\Delta \chi^2(1) = 0.50$, and the direct path from infancy to 11 years was non-significant.²

Continuity in Memory

In this domain, the latent variables for infancy and toddlerhood were indexed by measures representing immediate recognition, delayed recognition, and recall. The 11-year latent variable was indexed by 6 measures, 4 representing recognition (from the spatial recognition, pattern recognition, and immediate and delayed-match-to-sample tasks) and 2 representing recall (probe recall and name-face association). This model, shown in Fig 3, fit

²Because the psychomotor and encoding speed measures did not load together, separate models were evaluated for each type of speed. The encoding speed model fit adequately, but not as well as the one for psychomotor speed depicted in Fig 1: $\chi^2(8) = 11.75$, $p = .16$, RMSEA = .06, CFI = .88. While the loadings were all significant, .26 to .90 ($p < .01$), as was the path from infancy to toddlerhood ($\beta = .37$; $p < .05$), the path from toddlerhood to 11 years was only marginally significant ($\beta = .50$; $p < .10$), and the CFI fell below the commonly accepted cut-off of .90. Moreover, to achieve an adequate fit, the 12-month measure of encoding speed had to be dropped.

the data, with $\chi^2(117) = 166.58, p < .01$, RMSEA = .06, CFI = .91, RMSEA = .06, CFI = .91. The factor loadings ranged from .35 to .61 and were all significant at $p < .01$, with the exception of 7-month delayed recognition with $\lambda = .19$ (which was only marginally significant, $p < .10$). Paths from infancy to toddlerhood ($\beta = .88$) and toddlerhood to 11 years ($\beta = .50$) were both significant ($p < .05$), reflecting considerable stability in memory across age from infancy to 11 years. The indirect effect of infant memory on 11-year memory was .44 ($p < .001$). Here too, the alternative model did not differ from the original, $\Delta \chi^2(2) = 0.58$, while the direct path from infancy to 11 years was non-significant.

Continuity in Representational Competence

In this domain, the infancy and toddler latent variables were indexed by measures of cross-modal transfer, while the 11-year latent variable was indexed by three measures – cross-modal transfer, hidden patterns, and spatial relations. This model, shown in Fig 4, also fits the data well, with $\chi^2(12) = 17.87, p = .11$, RMSEA = .06, CFI = .92. Again, all loadings were positive and significant, with standardized factor loadings ranging from .29 to .96 ($p < .01$). The path from infancy to toddlerhood was marginal ($\beta = .39; p < .10$) and that from toddlerhood to 11 years was significant ($\beta = .36; p < .05$). For this domain, the indirect effect of infant representational competence on 11-year representational competence was .14 (ns). The direct path from infancy to 11 years was non-significant, and thus set to zero. Again, the alternative model here did not differ significantly from the original, $\Delta \chi^2(2) = 3.00$ and the direct path from infancy to 11 years was non-significant.

Two-group models

A 2-group model was tested for each domain to establish that the continuities shown in Fig 1–4 were not influenced by birth status. In these models, equality constraints were introduced across groups (preterms and full-terms) on factor loadings, variances and covariances among latent variables, and path coefficients. The results indicated that, for all four domains, the same continuity model fit well in both groups: Attention — $\chi^2(33) = 36.40, p = .31$, RMSEA = .05, CFI = .98; Processing Speed — $\chi^2(33) = 40.49, p = .17$, RMSEA = .06, CFI = .96; Memory — $\chi^2(254) = 306.84, p = .01$, RMSEA = .06, CFI = .84; Representational Competence — $\chi^2(32) = 29.97, p = .51$, RMSEA = .00, CFI = 1.00. In this last model, the equality constraint for one parameter (loading of 2-year cross-modal transfer on toddler representational competence) had to be dropped to achieve good fit.

Within-Domain versus Cross-Domain Relations

Because there were too few cases to use latent variables for comparisons involving multiple domains and multiple ages, latent factor scores (created from the continuity models) were used for this purpose. Latent factor scores were correlated with one another, both within and across domains (with average correlations calculated using Fisher r to z transformations). As shown in Table 4, the average within-domain correlations, which reflect continuity over age (.27 to .61; $M = .44$) were greater than cross-domain correlations (.06 to .25, $M = .15$). As one would expect, correlations were stronger over shorter time intervals; nevertheless, there was significant continuity over the 10 year time period from infancy to 11 years, in particular for speed and memory ($r = .29$ and .43, respectively). Additionally, there were several cross-domain relations, both within and across age. Notably, infant speed and attention both correlated significantly with 11-year memory.

Predicting 11-Year IQ

The same latent factor scores described above were also used in regressions exploring the relation between infant, toddler, and 11-year information processing to 11-year IQ. Of particular interest were (1) whether infant and toddler information processing would relate

to pre-adolescent IQ and (2) whether measures from the four domains would predict IQ independently of one another.

Initially, three simultaneous regression models were run, one at each age; the results are shown in Table 5. All were significant, with infant performance in the four domains accounting for 12.3 % of the variance in 11-year IQ, toddlerhood performance accounting for 17.5 %, and 11-year performance accounting for 45.2%. At all three ages, memory and representational competence contributed independently to the prediction of 11-year IQ; at 11 years, sustained attention also contributed independently of all other measures.

An additional hierarchical regression was run to show the cumulative amount of variance accounted for in the three waves of testing, and to determine whether the variance from earlier waves of testing was incorporated into later waves. In this regression, variables from infancy were entered first, as a set, those from toddlerhood were entered as a second set, and those from 11 years entered as a third set. The cumulative R^2 s at the three steps of this regression were 12.3%, 18.8%, and 47.2%, respectively. Here, the change in R^2 from infancy to toddlerhood, though significant $F(4, 122) = 2.41$ $p = .05$, was small (6.5%), indicating that most of the variance accounted for from toddlerhood was already present in infancy.

Discussion

Our results provide evidence of continuity for four domains of core cognitive abilities — attention, processing speed, memory, representational competence — from infancy (7 and 12 months), through toddlerhood (24 and 36 months), to pre-adolescence (11 years). They also provide evidence of how these infant and toddler abilities relate to later IQ. SEM models of continuity were fit to each of the four domains, using latent variables formed from data in each age period. All four models provided a good fit to the data, with significant paths from infancy → toddlerhood → 11 years. Latent factor scores derived from these models showed stronger cross-age correlations within domains (mean $r = .44$) than across domains (mean $r = .15$), suggesting that the infant mind is characterized by an early emerging constellation of abilities that endures.

This study includes three novel elements that extend previous research in important ways. First, it is the only prospective longitudinal study to measure performance in different domains simultaneously, and one of the few to examine continuities over such an extensive period — infancy to pre-adolescence (see also Fagan, Holland, & Wheeler, 2007; Sigman, Cohen, & Beckwith, 1997). By examining multiple domains in the same sample we avoid confounding cohort and domain differences. Second, this is the first study to use latent variables to examine continuities from infancy. Since latent variables extract the common variance that is shared among multiple tasks, we were able to minimize task-specific variance and measurement error (Friedman et al., 2006). Third, this is also the first study to examine the relative contributions of a variety of different abilities from infancy and toddlerhood to mature IQ. While we had previously shown that core abilities from infancy and toddlerhood predict MDI at 2 and 3 years (Rose, Feldman, Jankowski, & Van Rossem, 2005a, 2008b), here we showed that their predictive power extends into pre-adolescence. The infant, toddler, and contemporaneous 11-year measures accounted for 12.3%, 18.8%, and 47.2% of the variance in 11-year IQ, respectively.

Within-domain relations: Establishing Continuity for Information Processing Abilities from Infancy to 11 Years

This study extends previous research showing cross-age continuities in several important ways. First, our results replicate those of Rose et al. (Rose & Feldman, 1997; Rose,

Feldman, Futterweit, & Jankowski, 1997) which showed that immediate recognition memory at 7 and 12 months predicted memory at 11 years (see also Fagan et al., 2007; Sigman et al., 1997). They extend those earlier findings to other aspects of memory, namely, delayed recognition and recall, and to the toddler years (24 and 36 months), showing that that toddler memory bears similar relations to later memory. As the latent factor scores indicated, there was significant continuity not only from infancy to toddlerhood, and from toddlerhood to 11 years, but even across the entire 10-year period (infancy to 11 years, $r = .43$). Moreover, continuity models indicate that the infant-preadolescent memory relations are mediated by the toddler measures. These results support the contention that individual differences in memory emerge early and extend well into later childhood.

Second, the results extend those from Rose et al. (Rose, Feldman, Futterweit, & Jankowski, 1998) which showed that representational competence at 12 months predicted the same ability at 11 years. In the present study, we found that meaningful differences in this ability could be tapped at a younger age (7 months) and also in toddlerhood. Here the number of problems was increased, yielding more data points per child, half the cross-modal problems included at 11 years involved 180 degree rotations, which was not the case in the previous study. Moreover, the battery at 11 years included two visuo-spatial tasks that also involved mental rotation. Again, the latent factor scores indicated significant continuity from infancy to toddlerhood, and from toddlerhood to 11 years, with a marginally significant relation across the entire 10-year period (infancy to 11 years, $r = .15$). And again, the continuity model indicated that the infant-preadolescent relations were mediated by the toddler measures.

Third, this is the first investigation to show cross-age continuities over such extensive periods of time for attention and processing speed, two ‘cognitive primitives’ considered pivotal in the development of other aspects of cognition. Attention is important for the role it plays in gating information for further processing at multiple levels — from the perception of incoming stimuli, to encoding, to the control of actions (Posner & Rothbart, 2007). Processing speed is important for its relation, at older ages, to IQ (Detterman, 1987; Jensen, 1987), and for its association with individual differences in various higher level aspects of cognition, including fluid intelligence, reasoning, memory, and executive functioning (Anderson, 2001; Kail, 1986, 1988; Kail & Salthouse, 1994; Salthouse, 1996). The latent factor scores for attention and processing speed both indicated significant continuity from infancy to toddlerhood, and from toddlerhood to 11 years, with processing speed also showing significant continuity bridging the entire 10-year period — from infancy to 11 years ($r = .29$). As with the other two abilities, continuity models indicated that infant-preadolescent relations were mediated by the toddler measures.

Cross-Domain Relations: How Better Attention and Faster Processing Speed are Advantageous for the Development of Memory

The cross-domain associations of attention and processing speed to memory are in line with theoretical and empirical claims that speed spearheads the development of other aspects of cognition (Anderson, 2001). They are also consistent with the conceptualization of these associations by Fry and Hale (Fry & Hale, 1996) as developmental cascades, where age-related increases in processing speed serve to strengthen working memory, which, in turn, leads to greater cognitive competence in other areas. In the present study infant attention and speed were associated with toddler memory (as well as with 11-year memory), and toddler attention and speed were associated with 11-year memory. These results are also consistent with developmental cascades we have modeled, in which infant attention and processing speed influenced memory and representational competence, which then went on to influence 2- and 3- year MDI (Rose, Feldman, Jankowski, et al., 2005a; Rose et al., 2008b).

Predicting Pre-Adolescent IQ: The Role of Infant and Toddler Information Processing Abilities

Core information processing abilities are often thought to form the building blocks of more global aspects of cognition, such as IQ (Detterman, 1987). The present findings show that these same core abilities that had previously predicted 2- and 3-year MDI also predict 11-year IQ. A major strength of the present study is the use of multiple constructs at different ages, which allows for internal replication and a richer picture of the relative role of different early abilities for later cognition. With this approach, we were able to see that information processing abilities, whether assessed in infancy or toddlerhood maintain the same predictive relation to 11-year IQ, with memory and representational competence both exerting an independent influence.

Conclusion

This study provides some of the first evidence showing cognitive continuities from infancy to toddlerhood to pre-adolescence in four core domains –attention, processing speed, memory, and representational competence, and indicates how abilities from even the earliest ages are related to later IQ (see also Fagan et al., 2007; Sigman et al., 1997). These findings of continuity and prediction are rather remarkable, given the early ages of the initial assessments, the long predictive interval, and the important methodological differences between tasks used in infancy and pre-adolescence. The results reinforce the idea that the non-verbal methods and tasks, which are the hallmark of infant testing, can be used to probe aspects of cognition in infancy that are important harbingers of the same abilities seen years later. The ability to isolate such discrete abilities in infancy, coupled with their continuity and importance for later general ability, is likely to have profound implications for intervention.

Acknowledgments

This research was funded in part by Grants HD 13810 and HD 049494 from the National Institutes of Health. The authors are grateful to all the participants and their parents, and to Keisha Phillips for her invaluable help in testing children and scoring data.

References

- Anderson M. Annotation: conceptions of intelligence. *Journal of Child Psychology and Psychiatry and Allied Disciplines*. 2001; 42(3):287–298.
- Bauer PJ. Long-term recall memory: Behavioral and neuro-developmental changes in the first 2 years of life. *Current Directions in Psychological Science*. 2002; 11(4):137–141.
- Bauer PJ. Constructing a past in infancy: a neurodevelopmental account. *Trends in Cognitive Sciences*. 2006; 10:175–181. [PubMed: 16537115]
- 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]
- Browne, MW.; Cudeck, R. Alternative ways of assessing model fit. In: Bollen, KA.; Long, JS., editors. *Testing structural equation models*. Beverly Hills, CA: Sage; 1993. p. 136-162.
- DeFries, JC.; Plomin, R. *Origins of individual differences in infancy: The Colorado Adoption Project*. Orlando, Florida: Academic Press; 1985.
- Della Sala, S.; Gray, C.; Baddeley, A.; Wilson, L. *Visual patterns test: A test of short-term visual recall*. Bury St Edmunds: Thames Valley Test Company; 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.

- Diamond, A. Rate of maturation of the hippocampus and the developmental progression of children's performance on the delayed non-matching to sample and visual paired comparison tasks. In: Diamond, A., editor. *Development and neural bases of higher cognitive functions*: Vol. 608. *Annals of the New York Academy of Sciences*. New York: Academic Press; 1990. p. 394-426.
- Dougherty TM, Haith MM. Infant expectations and reaction time as predictors of childhood speed of processing and IQ. *Developmental Psychology*. 1997; 33:146-155. [PubMed: 9050399]
- Fagan JF. Memory in the infant. *Journal of Experimental Child Psychology*. 1970; 9:217-226. [PubMed: 5452116]
- Fagan, JF. Intelligence in infancy. In: Sternberg, RJ.; Kaufman, SB., editors. *The Cambridge handbook of intelligence*. New York: Cambridge University Press; 2011. p. 130-142.
- Fagan JF, Holland CR, Wheeler K. The prediction, from infancy, of adult IQ and achievement. *Intelligence*. 2007; 35:225-231.
- Fagan, JF.; Shepherd, P. *The Fagan Test of Infant Intelligence*. Cleveland, Ohio: Infantest Corp.; 1989.
- Fantz RL. Visual experience in infants: Decreased attention to familiar patterns relative to novel ones. *Science*. 1961; 146:668-670. [PubMed: 14191712]
- Friedman NP, Miyake A, Corley RP, Young SE, Defries JC, Hewitt JK. Not all executive functions are related to intelligence. *Psychological Science*. 2006; 17:172-179. [PubMed: 16466426]
- Fry AF, Hale S. Processing speed, working memory, and fluid intelligence: Evidence for a developmental cascade. *Psychological Science*. 1996; 7:237-241.
- Garrett HE. A developmental theory of intelligence. *American Psychologist*. 1946; 1:372-378. [PubMed: 20280373]
- Haith MM, Hazan C, Goodman GS. Expectation and anticipation of dynamic visual events by 3.5-month-old babies. *Child Development*. 1988; 59:467-479. [PubMed: 3359865]
- 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]
- Jensen, AR. Individual differences in the Hick paradigm. In: Vernon, PR., editor. *Speed of information-processing and intelligence*. Norwood, NJ: Ablex; 1987.
- Jöreskog, K.; Sörbom, D. *LISREL (Version 8.54)*: Scientific Software International. Inc.; 2003.
- Kail R. Sources of age differences in speed of processing. *Child Development*. 1986; 57:969-987. [PubMed: 3757612]
- Kail R. Developmental functions for speeds of cognitive processing. *Journal of Experimental Child Psychology*. 1988; 45:339-364. [PubMed: 3385355]
- Kail R, Salthouse TA. Processing speed as a mental capacity. *Acta Psychologica*. 1994; 86:199-225. [PubMed: 7976467]
- 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]
- 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 visual recognition memory: Infancy to 11 years. *Intelligence*. 1997; 24:381-392.
- 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. Dimensions of cognition in infancy. *Intelligence*. 2004a; 32:245-262.

- Rose SA, Feldman JF, Jankowski JJ. Infant visual recognition memory. *Developmental Review*. 2004b; 24:74–100.
- 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(3):231–250.
- Rose SA, Feldman JF, Jankowski JJ. Information processing in toddlers: Continuity from infancy and persistence of preterm deficits. *Intelligence*. 2009; 37:311–320. [PubMed: 20161244]
- Rose SA, Feldman JF, Jankowski JJ, Caro DM. A longitudinal study of visual expectation and reaction time in the first year of life. *Child Development*. 2002; 73:47–61. [PubMed: 14717243]
- Rose SA, Feldman JF, Jankowski JJ, Van Rossem R. Pathways from prematurity and infant abilities to later cognition. *Child Development*. 2005a; 76(6):1172–1184. [PubMed: 16274433]
- Rose SA, Feldman JF, Jankowski JJ, Van Rossem R. Pathways from prematurity and infant abilities to later cognition. *Child Development*. 2005b; 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*. 2008a; 36:367–378. [PubMed: 19122757]
- Rose SA, Feldman JF, Jankowski JJ, Van Rossem R. A cognitive cascade in Infancy: Pathways from prematurity to later mental development. *Intelligence*. 2008b; 36(4):367–378. [PubMed: 19122757]
- Rose SA, Feldman JF, Jankowski JJ, Van Rossem R. Basic information processing abilities at 11 years account for deficits in IQ associated with preterm birth. *Intelligence*. 2011; 39:198–209. [PubMed: 21643482]
- Rose SA, Feldman JF, Wallace IF. Infant information processing in relation to six-year cognitive outcome. *Child Development*. 1992; 63:1126–1141. [PubMed: 1446544]
- Rose SA, Feldman JF, Wallace IF, McCarton C. Information processing at 1 year: Relation to birth status and developmental outcome during the first five years. *Developmental Psychology*. 1991; 27:723–737.
- Salthouse TA. The processing-speed theory of adult age differences in cognition. *Psychological Review*. 1996; 103:403–428. [PubMed: 8759042]
- Sigman M, Cohen SE, Beckwith L. Why does infant attention predict adolescent intelligence? *Infant Behavior and Development*. 1997; 20:133–140.
- Sigman M, Cohen SE, Beckwith L, Asarnow R, Parmelee AH. Continuity in cognitive abilities from infancy to 12 years of age. *Cognitive Development*. 1991; 6:47–57.
- Thompson LA, Detterman DK, Plomin R. Associations between cognitive abilities and scholastic achievement: Genetic overlap but environmental differences. *Psychological Science*. 1991; 2:158–165.

Highlights

- Cognitive continuities were found across four domains from infancy to 11 years: attention, processing speed, memory, and representational competence.
- Continuities in each domain fit SEM models proposing *infant abilities* → *toddler abilities* → *11-year abilities*.
- Infant, toddler, and 11-year information processing accounted for 12.3%, 18.5%, and 45.2%, respectively, of the variance in 11-year IQ.
- The roots of later cognition can be identified in infancy.

Figure 1.

Structural equation model of continuity in attention: Infancy → toddlerhood → 11 years. Ovals represent latent variables; rectangles represent observed variables. Single-headed arrows between ovals represent path coefficients; those from ovals to rectangles represent factor loadings. Numbers with arrows pointing to rectangles and ovals are error terms. Parameter estimates are shown for the completely standardized solution. All path coefficients and factor loadings are significant ($p < .05$).

Figure 2.

Structural equation model of continuity in processing speed: Infancy → toddlerhood → 11 years. All path coefficients and factor loadings are significant ($p < .05$).

Figure 3.

Structural equation model of continuity in memory: Infancy → toddlerhood → 11 years. All path coefficients and factor loadings are significant ($p < .05$), with the exception of the loading of 7-month delayed recognition on the infant factor, which was marginal ($p < .10$).

Figure 4.

Structural equation model of continuity in representational competence: Infancy → toddlerhood → 11 years. All path coefficients and factor loadings are significant ($p < .05$).

Table 1

Descriptive Statistics for Infant and Toddler Measures

Information Processing Measures	7 Months		12 Months		24 Months		36 Months	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
<i>Memory</i>								
Immediate Recognition (% novelty)	59.39	5.10	58.98	4.47	57.84	4.09	59.02	5.39
Delayed Recognition (% novelty)	56.11	5.98	54.47	6.46	58.08	6.93	62.59	7.48
Recall (% targets reproduced in correct order)	----	----	38.07	19.40	56.63	20.92	75.37	17.51
<i>Processing Speed</i>								
Encoding speed (trials to criterion) ^a	17.50	10.90	10.83	7.91	9.19	5.35	20.57	10.92
Psychomotor speed — RT (ms)	329.45	38.03	294.39	31.36	233.08	29.90	218.36	26.16
<i>Attention</i>								
Look duration (mean of standardized scores) ^b	.05	.66	.01	.62	-.03	.62	-.01	.61
Shift rate (mean of standardized scores) ^b	.04	.74	-.02	.69	-.06	.69	-.04	.76
<i>Representational Competence</i>								
Tactual-visual cross-modal transfer (% novelty)	48.95	5.37	48.45	4.70	48.93	5.15	47.90	5.25
Anticipations (%)	16.24	12.48	24.98	15.33	15.54	10.96	20.34	12.48

Note 1. $N = 113-131$ (The sample is restricted to those who returned for follow-up at 11 years.)

Note 2. Since the parameters of many tasks were adjusted to make them age-appropriate, developmental change cannot be computed on these data.

^aChildren took longer to reach criterion at 36 than 24 months because trial times were shorter and the criterion more stringent.

^bRestricting the sample to those who had data at 11 years resulted in the mean of standardized scores deviating slightly from zero.

Table 2

Descriptive Statistics for 11-Year Measures

Information Processing Measures	<i>M</i>	<i>SD</i>
<i>Memory</i>		
Pattern Recognition (% correct)	82.98	11.36
Delayed Match-to-Sample (# correct)	77.50	12.02
Spatial Recognition (% correct)	78.73	11.09
Probe Recall (% correct)	41.11	6.42
Name-Face Association (# correct)	4.05	1.91
<i>Processing Speed</i>		
Tachistoscopic Threshold (ms)	136.62	68.19
Reaction Time (ms)	553.66	116.74
Match-to-Sample (# correct minus incorrect)	12.24	3.90
<i>Attention</i>		
Rapid Visual Processing (# false alarms)	3.52	4.10
Rapid Visual Processing (# hits)	20.03	3.16
Span of Apprehension (# correct)	74.63	10.65
<i>Representational Competence</i>		
Tactual-visual cross-modal transfer—rotated (# correct)	4.84	1.80
Spatial Relations (#correct)	10.29	6.43
Hidden Patterns (# correct minus incorrect)	22.77	10.75
<i>Intelligence(WISC-III)</i>		
Full Scale IQ scores	92.05	13.34

Note 1 – *N* = 131.

Table 3

Within-domain correlations among individual measures and IQ

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Attention																	
1 Looks – 7 mo	.34	.78	.31	.20	.19	.14	.15	.09	.25	.19	.10						
2 Looks – 12 mo		.42	.75	.30	.36	.22	.22	.17	.08	.05	-.07						
3 Shifts – 7 mo			.38	.27	.27	.25	.21	.01	.08	.13	.01						
4 Shifts – 12 mo				.27	.29	.28	.32	.17	.12	.09	.08						
5 Looks – 2 yr					.38	.82	.32	.21	-.16	.02	.06						
6 Looks – 3 yr						.48	.78	.20	.30	.31	.14						
7 Shifts – 2 yr							.53	.20	-.13	.05	.07						
8 Shifts – 3 yr								.20	.28	.29	.15						
9 SOA – 11 yr									.18	.28	.26						
10 RVP (False Alarms) – 11 yr										.45	.38						
11 RVP (Hits) – 11 yr											.39						
12 Full-Scale IQ – 11 yr																	
Processing Speed																	
1 Reaction Time – 7 mo	.31	.44	.40	.14	.03	.09	.04										
2 Reaction Time – 12 mo		.37	.20	.20	.06	.08	.17										
3 Reaction Time – 2 yr			.59	.14	.29	.11	.06										
4 Reaction Time – 3 yr				.23	.20	.08	.10										
5 Reaction Time – 11 yr					.34	.22	.29										
6 Tach. Thresh. – 11 yr						.26	.33										
7 Perceptual Speed – 11 yr							.55										
8 Full-Scale IQ – 11 yr																	
Memory																	
1 Recognition – 7 mo	.28	.27	.15	.18	.28	.32	.24	.16	.09	.08	.03	.20	.04	.10	.24	.04	.22
2 Recognition – 12 mo		.05	.14	.06	.19	.33	.12	.28	.09	.12	.12	.12	-.05	.00	.09	.12	.13
3 Delayed Recognition – 7 mo			-.07	.04	.10	-.05	.11	-.08	.07	.04	.01	.02	-.07	.10	.09	.14	.12

\$watermark-text

\$watermark-text

\$watermark-text

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
4 Delayed Recognition – 12 mo				.23	.12	.23	.21	.24	.13	.04	.09	.10	.09	.02	-.07	.00	.00
5 Recall – 12 mo					.15	.09	.15	.11	.16	.30	.21	.18	.17	.09	.16	.20	.18
6 Recognition – 2 yr						.35	.29	.12	-.05	.12	.14	.17	.15	.11	.03	.01	.27
7 Recognition – 3 yr							.38	.14	.07	.10	.26	.17	.12	.07	.07	.05	.22
8 Delayed Recognition – 2 yr								.23	.04	.21	.22	.19	.09	.13	-.04	.02	.21
9 Delayed Recognition – 3 yr									.18	.16	.23	.08	-.01	.04	-.02	.03	.04
10 Recall – 2 yr										.41	.14	.19	.17	.02	.22	.13	.13
11 Recall – 3 yr											.34	.32	.31	.14	.21	.12	.32
12 Pattern Recognition I – 11 yr												.27	.36	.27	.35	.27	.27
13 Pattern Recognition II – 11 yr													.35	.37	.28	.30	.34
14 Spatial Recognition – 11 yr														.25	.31	.28	.24
15 Delayed Match – 11 yr															.34	.17	.30
16 Probe Recall – 11 yr																.26	.39
17 Name Face – 11 yr																	.20
18 Full-Scale IQ – 11 yr																	

Representation Competence

1 Cross-modal Transfer – 7 mo	.25	.04	.16	.01	.15	-.02	.12										
2 Cross-modal Transfer – 12 mo		.11	.26	.22	.14	.11	.28										
3 Cross-modal Transfer – 2 yr			.29	.16	.00	-.06	-.02										
4 Cross-modal Transfer – 3 yr				.13	.25	.23	.33										
5 Cross-modal (rotated) – 11 yr					.20	.22	.33										
6 Hidden Figures – 11 yr						.50	.50										
7 Spatial Relations – 11 yr																	
8 Full-Scale IQ – 11 yr							.43										

Note. $N = N = 100 - 131$; correlations are partialled for prematurity. Abbreviations: SOA –Span of apprehension: RVP – Rapid visual processing. Correlations of .18 are significant at $p < .05$; correlations of .24 are significant at $p < .01$. All measures are scaled so that high scores indicate better performance.

Table 4
Within-domain and cross-domain correlations among latent factor scores and 11-year IQ

Attention											
Infant	Toddler	11 Yr	Infant	Toddler	11 Yr	Infant	Toddler	11 Yr	Infant	Toddler	11 Yr
Speed											
Infant		.12	.24**	.35***	.15†	.24**	.24**	.17*	-.04	-.04	.07
Toddler		.28**	.15†	.20*	.19*	.17*	.17*	.12	.05	.08	.04
11 Yr			.18*	.13	.48***	.07	.15†	.31***	.09	.08	.29**
Average		r = .28**		r = .23**			r = .18*			r = .07	
Memory											
Infant				.75***	.29***	.21*	.26**	.27**	-.10	-.09	.17†
Toddler					.39***	.20*	.23**	.23**	-.07	-.08	.14
11 Yr						.19*	.21*	.39***	.11	.10	.38***
Average				r = .51***			r = .25**			r = .06	
Representational Competence											
Infant							.78***	.43***	.14†	.11	.17*
Toddler								.54***	.20*	.05	.26**
11 Yr									.21*	.03	.34***
Average							r = .61***			r = .17*	
Representational Competence											
Infant										.48**	.15†
Toddler											.32***
11 Yr											
Average										r = .32**	

\$watermark-text

\$watermark-text

\$watermark-text

			<i>Attention</i>			<i>Speed</i>			<i>Memory</i>			<i>Representational Competence</i>		
			Infant	Toddler	11 Yr	Infant	Toddler	11 Yr	Infant	Toddler	11 Yr	Infant	Toddler	11 Yr
11-Yr Full-Scale IQ			.03	.12	.40***	.12	.10	.45***	.25**	.29***	.43***	.26**	.31**	.54**

Note. Attention, 11 Yrs 1=sustained attention; 11 Yrs 2=selective attention.

$\dagger$ p .10;
* p .05;
** p .01;
*** p .001

Table 5

Simultaneous Multiple Regressions: Predicting 11-year IQ from Latent Factor Scores Representing Information Processing in Four Domains

<i>Predicting from Infancy</i>	B
Attention	-.03
Processing Speed	.11
Memory	.19 *
Representational Competence	.24 **
$R = .35^{**} R^2 = .12^{**}$	
<i>Predicting from Toddlerhood</i>	B
Attention	.04
Processing Speed	.05
Memory	.26 **
Representational Competence	.30 ***
$R = .42^{***} R^2 = .18^{***}$	
<i>Predicting from 11 Years</i>	B
Attention	.20 **
Processing Speed	.15 †
Memory	.19 **
Representational Competence	.37 ***
$R = .66^{***} R^2 = .43^{***}$	

†
p < .10;

*
p < .05;

**
p < .01;

p < .001