Published in final edited form as:

Child Dev. 2013 January ; 84(1): 154–162. doi:10.1111/j.1467-8624.2012.01849.x.

Systems and Cascades in Cognitive Development and Academic Achievement

Marc H. Bornstein, Chun-Shin Hahn, and Dieter Wolke

Abstract

A large-scale ($N = 552$) controlled multivariate prospective 14-year longitudinal study of a developmental system showed that information-processing efficiency in infancy (4 months), general mental development in toddlerhood (18 months), behavior difficulties in early childhood (36 months), psychometric intelligence in middle childhood (8 years), and maternal education either directly or indirectly (or both) contribute to academic achievement in adolescence (14 years).

... what's past is prologue; what to come, In yours and my discharge.

Antonio in W. Shakespeare's *The Tempest*, Act 2, scene 1, lines 247-248.

Two key considerations in contemporary developmental science are, one, the trajectory through time of domain-related age-appropriate constructs toward a mature phenotype within that developmental domain and, two, the relative contributions of multiple determinants from different domains to the expression of a mature phenotype. The first concern is captured in diverse forms of developmental stability, including cascades, and second in developmental systems. In this study, we braid these two central considerations and use adolescent academic achievement as their convergent phenotypic endpoint.

Based on the ecological developmental perspective (Bronfenbrenner & Morris, 2006), dynamic systems theory emphasizes the advantages in understanding that are gained from simultaneous consideration of the independence and interdependence of multiple organismic and environmental determinants in predicting development. The present study assesses the contributions of an ecologically comprehensive suite of determinants in early life to predict adolescent academic achievement and employs a systems framework that included endogenous (information processing, temperament, behavior difficulties) as well as exogenous factors both distal (maternal education) and proximal (e.g., enriched parenting, home environment) to the child that are believed directly or indirectly or both to relate to academic achievement.

The extant literature concerning endogenous and exogenous sources of influence on cognitive development is rich. However, few research efforts have incorporated factors from multiple domains simultaneously to identify their independent and interdependent effects. Thus, the unique and combined contributions that each source may make to development are essentially unexplored, and the overlap of different factors vis-à-vis unique contribution of any one remains unknown. Here, we evaluated a systems model of hypothesized relations among factors deriving from the child, the mother, and the context. Embedded in our systems model was a developmental cascade of cognitive functions per se. Developmental

cascades consider that early determinants initiate spreading effects across a domain that eventuate in distal phenotypic performance. We see “value added” from melding cascades in systems. Rather than assuming that a given determinant directly predicts a distal criterion, we believe tests of indirect paths between predictors and criterion are more sensitive, powerful, and theoretically appropriate (Shrout & Bolger, 2002).

This multivariate longitudinal study began in infancy. Contemporary psychological theories conceptualize human beings as information processors, and information processing starts at birth in infants’ efforts to make sense of their environment and gain mastery over it. Individual differences in information processing account for variation in cognition (Davis & Anderson, 2001), and extant longitudinal assessments of infant information processing have pointed to its predictive value for intelligence test performance and academic achievement (Bornstein, 1985a, 1998; Colombo, 2004; Kavšek, 2004). One way to access information processing in infants is through habituation (Bornstein, 1985b). Additionally, scoring well on mental tests in childhood and achieving academically in adolescence reflect temperament and personality (Pasilin, 1986; Sternberg, Grigorenko, & Bundy, 2001; Zigler, Abelson, & Seitz, 1973), and behavior difficulties undermine children’s testing, cognition, and achievement (Caprara, Barbaranelli, Incatasciato, Pastorelli, & Rabasca, 1997; Masten et al., 2005; Moffitt et al., 2011; Odgers et al., 2008). Effective and consistent features of the environment also exert positive influences over cognition and achievement: Maternal education is a robust predictor of child cognitive functioning and school outcome (Hoff & Tian, 2005; Schneider, Wolke, Schlagmuller, & Meyer, 2004; Walker, Greenwood, Hart, & Carta, 1994); enriched parenting contributes to cognitive development (Bornstein, 1985a); and the home environment relates to later achievement (Bradley & Caldwell, 1984; Tong, Baghurst, Vimpani, & McMichael, 2007).

In a nutshell, we tested a systems model that included information processing, personological, social, and environmental factors. A large-scale multivariate longitudinal study is positioned to unveil complex developmental patterns that predict academic achievement.

METHOD

Participants

This investigation was conducted as part of the Avon Longitudinal Study of Parents and Children (Golding, Pembrey, Jones, & ALSPAC Study Team, 2001). All births in the former Avon Health Authority with an expected date of delivery between 1 April 1991 and 31 December 1992 were eligible, including > 80% of 14,138 surviving live births from that geographic catchment area. Potential participants for this study were 983 singletons and mothers in the “10% sample” which underwent intensive assessment. Elimination and attrition occurred for failures to habituate ($n = 351$), computer or experimenter errors ($n = 7$), and fussiness ($n = 19$); 20 more infants were excluded due to preterm (gestation at delivery < 37 weeks; $n = 17$) or postterm (gestation at delivery > 43 weeks, $n = 3$) delivery (both relate to diminished academic achievement; Kavšek & Bornstein, 2010; MacKay, Smith, Dobbie, & Pell, 2010). From 586 remaining term infants, 571 who were of normal birth weight (> 2500 g) were included. Nineteen additional infants were excluded because of diagnoses of developmental problems during the 14 years (e.g., autism, cerebral palsy). The final sample consisted of 552 term (M gestation = 39.85 weeks, $SD = 1.21$), healthy, and normal birth weight ($M = 3539.50$ g, $SD = 460.44$) infants, 243 girls and 309 boys. All participated in the habituation procedures, did not fuss, and achieved habituation. Table 1 presents their sociodemographic characteristics.

System and Cascade Constituents

Testers and coders at each wave were blind to children's performance and other data at other waves.

4 months: Habituation efficiency—Infants participated in an infant-controlled habituation: Each trial began when the infant looked at the stimulus and ended when the infant looked away for at least 2 s continuously, and the infant was judged to have habituated (achieved criterion) when the duration of looking on any two successive trials (after trial 2) was less than one-half the total duration of any two previous successive trials. The habituation stimulus was a black-on-white geometric pattern of 4 diamonds subtending 26° (height) X 20° (width). Each infant who habituated then saw 4 paired test trials, each continuing until 10 s of looking had accumulated. On test trials, the habituation stimulus was paired with a same-size novel stimulus, a random polygon; the two were equidistant from the center. Identical novel prehabituation and posttest stimuli sandwiched the habituation-test sequence.

The final sample of 552 infants was categorized as completers ($n = 370$), infants who habituated to criterion and then amassed 40 s of looking on the test, and part-completers ($n = 182$), infants who habituated but ended the session before the test was completed. Experimental controls ruled out alternative response fatigue and sensory adaptation interpretations of habituation: Infants who completed all procedures showed a novelty response to the new versus the habituation stimulus in the test, $t(360) = 25.54$, $p < .001$, $d = 1.34$, and looked equally at the prehabituation and posttest stimuli, $t(368) = 1.11$, $p = .27$, $d = 0.06$.

Habituation efficiency (total looking time to reach habituation criterion $\times -1$) was used as the outcome measure because it was available for both completers and part-completers. A sub-group of this sample has given evidence of 2-week reliability of habituation efficiency (Bell, Slater, & ALSPAC Study Team, 2002), $r = .43$, $p < .05$, 95% CI = (.08, 1.00); see also Colombo, Shaddy, Richman, Maikrantz, and Blaga (2004).

6 months: Temperament—The Infant Temperament Questionnaire (ITQ; Carey & McDevitt, 1978) assessed infant temperament. The average internal consistency reliability for the ITQ is .83, and test-retest reliability (16 to 47 days) is .86. A principal axis factoring score was computed using Rhythmicity, Approach, Adaptivity, Intensity, and Mood on the ITQ following Carey and McDevitt's (1978) diagnostic clusters of "difficult" temperament.

6 months: Enriched parenting—Mothers reported their parenting practices in terms of how often, for example, they read a story or showed pictures in books and played with toys and imitation games with their children on a 5-point scale (*nearly every day* to *never*). Item scores (reverse coded) were summed to create an enriched parenting score.

6 months: Home environment—Cognitive environment of the home was measured with modified forms of the Home Observation for Measurement of the Environment (HOME; Bradley, 2009), including subscales: maternal responsiveness, acceptance of child, organization of the environment, provision of appropriate play materials, involvement with child, variety of stimulation in the home, language stimulation, and encouragement of social maturity. Internal consistency is .89 for the total HOME (Bradley & Caldwell, 1984).

18 months: Griffiths—Trained psychologists administered the standardized Griffiths (1984) Mental Development Scales to assess 5 major areas of development: locomotor, personal-social, hearing and speech, hand and eye coordination, and performance. Total

scores for each subscale show internal consistency (corrected split-half method), ranging from .91 to .97 (<http://www.hogrefe.co.uk/>). Scores were age adjusted and averaged to form an individual General Developmental Quotient (GQ).

36 months: Behavior difficulties—The Strengths and Difficulties Questionnaire (SDQ; Goodman, 1997, 2001; Van Roy, Veenstra, & Clench-Aas, 2008) assessed child behavior difficulties. The average internal consistency reliability estimate is .73, and test-retest reliability (4 to 6 months) is .62 (Goodman, 2001). A total behavior difficulties score was obtained by summing Hyperactivity, Emotional Symptoms, Conduct Problems, and Peer Problems scale scores (www.sdqinfo.org).

8 years: WISC—Trained testers administered the WISC-III^{UK} (Wechsler, Golombok, & Rust, 1992), an assessment of psychometric intelligence standardized on a sample of 2,200 children aged 6 to 16 years. Average internal consistency reliability coefficients and test-retest stability coefficients are > .95 for Full Scale IQ (Wechsler, 1991).

14 years: Academic achievement—In the United Kingdom, the National Curriculum is defined in five key stages. At the end of Key Stage 3 (covering the first 3 years of secondary school), standardized tests in English, Mathematics, and Science are carried out nationally. Data were retrieved from the National Pupil Database of the Department for Children, Schools, and Families via record linkage. Total scores were used as measures of adolescent academic achievement in each subject.

Maternal education—Mothers provided information on their educational qualifications.

Preliminary Analyses and Analytic Plan

Univariate distributions for all variables were examined for nonnormalcy and outliers (Fox, 1997). To approximate normalcy and reduce the number and influence of outliers, habituation efficiency was re-expressed using a $\log_{10}$ transformation, the Griffiths GQ was raised to the fourth power, and the child behavior difficulties score was re-expressed using a cube-root. Bivariate plots based on pair-wise deletion procedures confirmed that all variables were linearly related. Missing data points (24.43% of the total data in the total sample) were imputed using a two-stage Expectation-Maximization estimation of the structured model and the Maximum likelihood function (Jamshidian & Bentler, 1999).

We used structural equation modeling (SEM; Bentler, 1995; Bentler & Wu, 1995) to assess unique relations among habituation efficiency, child socioemotional functioning, enriched parenting, home environment, maternal education, child cognitive development, and adolescent achievement controlling for other predictors in the model. Guided by the literature, we expected that more efficient habituation in infancy would eventuate in more advanced academic achievement in adolescence through a developmental cascade of intervening cognitive functions. To evaluate the significance of regression coefficients in the final models, we report the standardized coefficients and appraise their probabilities using the critical ratios associated with the robust standard errors for the unstandardized coefficients (one-tailed tests). Model fit was assessed using the robust Yuan-Bentler scaled chi-square statistic, robust comparative fit index, the standardized root mean squared residual (Browne & Cudeck, 1993), and the root mean square error of approximation and its 90% confidence interval. Cutoff values $\sim .95$ for CFI and $\sim .09$ and $.06$ for SRMR and RMSEA, respectively, are indicative of a relatively good fit between the hypothesized model and observed data. To enhance the cross-validation adequacy of models, the Akaike Information Criterion (Akaike, 1987; Kaplan, 2000) was monitored for its decreasing value in all nested models. To specify the systems model direct paths between endogenous and

exogenous variables and child cognitive and achievement outcomes were added to the model if their associations at the zero-order level were significant; non-significant paths were eliminated sequentially based on multivariate Wald statistics.

To provide accurate estimates of true relations among the underlying constructs measured, we conducted a follow-up analysis that corrected observed correlations for attenuation due to random measurement error. The correction for attenuation due to unreliability used Spearman's (1904) attenuation formula. The reliability estimates to compute the attenuation-corrected coefficients were: .43 for habituation efficiency (Bell et al., 2002), .83 for the ITQ (Carey & McDevitt, 1978), .89 for the modified Home score (Bradley & Caldwell, 1984), .94 for Griffiths (<http://www.hogrefe.co.uk/>), .73 for SDQ (Goodman, 2001), and .95 for the WISC-III (Wechsler, 1991). Because reliability estimates were not available for maternal enriched parenting and education, or the UK Key Stage 3 national standardized tests, the attenuation-corrected covariance matrix for SEM input was not corrected for these variables. We used imputed estimates of sample covariance matrix based on the structured model from EQS output to compute the attenuation-corrected coefficients. This attenuation-corrected covariance matrix was then used as the input for SEM analysis. (The uncorrected pairwise covariance matrices and the corrected imputed covariance matrices for the total sample and completers are available from the first author.)

Models were evaluated in both the total sample (completers and part-completers, $N = 552$) and completers ($n = 370$), and similar results were obtained. Reported results are based on the total sample.

RESULTS

Table 2 lists the *M*s, *SD*s, and numbers of observations for all measures. The resulting final sample was generally reflective of the population as indicated by standard deviations of the standardized measures.

We fit a measurement model of adolescent academic achievement with Mathematics as the marker indicator. In a saturated model with 0 *df*, the factor loadings for English, Mathematics, and Science on the 14-year academic achievement latent variable were .61, .69, and .46, respectively, $ps < .001$. The error variance of English was later fixed to avoid fitting a just-identified model: A model in which English, Mathematics, and Science all loaded, without covarying errors, on a single Academic Achievement latent variable fit the data well: Y-B $\chi^2(1) = 0.13$, $p = .72$, Robust CFI = 1.00, SRMR = .01, RMSEA = .00. Factor loadings for English, Mathematics, and Science on the 14-year academic achievement latent variable were .59, .70, and .46, respectively, $ps < .001$.

Developmental Systems and Cascades

Figure 1 shows the final cascade and systems model. Child difficult temperament, maternal parenting, and the modified HOME score were omitted from the model because they did not relate to any of the outcome measures when evaluated simultaneously with other predictors in the model. This final model fit the data well: Y-B $\chi^2(16) = 26.87$, $p = .04$, Robust CFI = 1.00, SRMR = .05, RMSEA = .00, 90% CI = (.00, .02). Controlling for other predictors in the model, the developmental cascade showed that children who habituated more efficiently at 4 months and scored higher on the Griffiths at 18 months had higher IQs at 8 years and academic achievement scores at 14 years. The indirect effects of habituation efficiency and interim cognitive measures on the 14-year English, Mathematics, and Science tests were all significant at $p < .05$ or better. Children who scored lower on the Griffiths at 18 months had more behavioral difficulties at 36 months, and behavior difficulties had unique negative direct effects on IQ at 8 years and academic achievement at 14 years. Maternal education

had unique positive direct effects on Griffiths at 18 months, IQ at 8 years, and academic achievement at 14 years. IQ at 8 years uniquely predicted 14-year academic achievement.

Total, Direct, and Indirect Effects

Figure 2 summarizes the relative effects of cognitive domain predictors, child behavior difficulties, and maternal education on adolescent academic achievement. The total effects on adolescent academic achievement were for habituation efficiency: the .03 ($p < .01$) indirect effect through the cognitive cascade; for the Griffiths: the .25 ($p < .001$) indirect effect mediated by IQ at 8 years and by behavior difficulties; for child behavior difficulties: the $-.21$ ($p < .001$) direct plus indirect effects mediated by IQ at 8 years = $-.14$ ($p < .01$); for maternal education: the .25 ($p < .001$) direct plus indirect effects mediated by the Griffiths and through the cognitive cascade, and by IQ at 8 years = .26 ($p < .001$); and for IQ at 8 years: the .64 ($p < .001$) direct effect and.

Follow-up analysis with attenuation-corrected coefficients indicated that the total effects on adolescent academic achievement were for habituation efficiency: the .06 indirect effect through the cognitive cascade; for the Griffiths: the .29 indirect effect mediated by IQ at 8 years and by behavior difficulties; for child behavior difficulties: the $-.25$ direct plus indirect effects mediated by IQ at 8 years = $-.17$; for maternal education: the .24 direct plus indirect effects mediated by Griffiths and through the cognitive cascade, and by IQ at 8 years = .27 (all $ps < .001$); and for IQ at 8 years: the .64 direct effect and.

DISCUSSION

Many endogenous and exogenous factors influence cognitive development and academic achievement. We identified direct and indirect effects of cognitive predictors as well as intrapersonal noncognitive characteristics and extrapersonal factors. In our resultant systems models, IQ had the largest (total) effect on adolescent academic achievement, followed by maternal education, child behavior difficulties, Griffiths, and habituation efficiency. Intelligence has long been believed to be the best single predictor of many criteria of success in life (Hunter & Hunter, 1984; Schmidt, Ones, & Hunter, 1992), educational achievement among them (Brody, 1997; Ceci & Williams, 1997; Sternberg et al., 2001). As we found here general cognitive ability, captured by childhood IQ, is strongly linked with academic achievement in the humanities and sciences during adolescence (Cronbach & Snow, 1977). In the Fels longitudinal study, too, IQs between 3 and 18 years of age predicted attained education and occupational status after 26 years of age (McCall, 1977).

Four age-appropriate cognitive constructs relate uniquely from one to the next across time from infancy into adolescence. This cascade revealed significant (if modest) consistency in human mental development even when controlled for other personal proclivities in children (difficult temperament and behavior difficulties) as well as relevant proximal and distal factors exogenous to children (maternal education, enriched parenting, and the home environment). Specifically, information-processing efficiency in infancy predicted a small but significant degree of cognitive status across childhood and academic achievement in adolescence, and this predictive connection appeared to reside in children themselves. The findings are consistent with a model of development where early emerging cognitive abilities constitute a foundation and monophthongal building blocks for successive steps of functioning. To our knowledge, only two other studies of the predictive ability of information processing have begun so early or extended so long, and both arrived at similar conclusions (Fagan, Holland, & Wheeler, 2007; Sigman, Cohen, & Beckwith, 1997).

Behavior difficulties at 3 years undermined academic achievement even after other factors were taken into account. Externalizing is associated with poorer cognitive functioning and

school attainment (Caprara et al., 1997; Odgers et al., 2008). This finding articulates with a lack-of-control factor that Moffitt and colleagues (2011) identified at 3 years of age in the Dunedin sample that also turned out to be a negative predictor of academics as well as health, wealth, and public safety. Some variation in human intelligence and achievement may be attributable to genetic factors (Posthuma et al., 2005) which we did not measure. In this regard, however, it is noteworthy that temperament assessed at 6 months was not a predictor of later academic achievement controlling for other predictors in our systems model. Among factors extrapersonal to the children, maternal education (reflecting, presumably, both social and genetic transmission of cognitive ability) held some predictive value for toddler general mental development, child intelligence, and adolescent academic achievement.

Piaget (1953) theorized that infant mental life stands discontinuously apart, an assertion that Bayley (1949) buttressed with empirical data. Together, these two 20th century developmentalists fortified certain views of intelligence, infancy, and development--that intelligence at different stages of life qualitatively varies, that infant mental life stands apart from mental life in the balance of the life course, and that development is unstable. Our large-*N*, normative, prospective, long-term, longitudinal, multivariate study demonstrates quantitative stability in intelligence and that individual differences in infant information processing initiate a connected cascade across age-appropriate cognitive abilities at least into adolescence. Very young infants possess an active mental life which they bring to their own long-term development. However, infant habituation performance does not fix a child's psychometric intelligence or an adolescent's academic achievement separate from his or her personality and experiences. Our systems analyses revealed independent and unique contributions of other endogenous and exogenous factors in the unfolding of cognitive development toward academic achievement.

Conceptualizing cognition from infancy in terms of developmental systems and cascades has several implications. First, it has meaning for developmental science in describing the growth of individuals with greater fidelity. Stability in information-processing abilities appears to undergird cognitions across important developmental transformations from the first half of the first year into the second decade of life. Second, it helps toward more comprehensively understanding the nature and structure of intelligence and the multiple roots of academic achievement. No single factor emerged as the sole predictor of academic achievement, and so important aspects of cognitive attainment appear to be developmentally assured in many ways. From an evolutionary perspective, development is protected when there are many genetic and experiential determinants. Third, the findings may have implications for the early identification of and intervention with children born at risk (Kavšek & Bornstein, 2010). Upstream interventions aimed at improving information processing and mitigating behavioral difficulties (Bornstein & Tamis-LeMonda, 1994) may affect downstream intelligence, cognition, and achievement.

Key designs in developmental science are *longitudinal* because only they can address stability and continuity and *systemic* because only they can document the independent and interdependent influences of multiple characteristics and experiences. In this study, we combined the two and learned that infant abilities, proclivities, and experiences shape toddler and child cognitive development which in turn influence adolescent academic achievement. Developmental science carries three burdens of description (*hard*), explanation (*difficult*), and prediction (*nearly impossible*). Here, we attempted to render the impossible merely difficult.

Acknowledgments

We thank the mothers who took part in the ALSPAC; the midwives for their cooperation and help; J. C. Bell, J. Golding, C. Padilla, D. Putnick, and A. Slater; and the Medical Research Council, the Wellcome Trust, UK government departments, medical charities, and others for financial support. The ALSPAC Study Team comprises interviewers, computer technicians, laboratory technicians, clerical workers, research scientists, volunteers, and managers. This research was supported in part by the Intramural Research Program of the NIH, NICHD. Marc H. Bornstein and Chun-Shin Hahn, Child and Family Research, Eunice Kennedy Shriver National Institute of Child Health and Human Development. Dieter Wolke, Department of Psychology and Health Science Research Institute, University of Warwick, Coventry (UK).

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Total sample, $N = 552$ ** $p < .01$; *** $p < .001$.**Figure 1.**

Standardized solution for cascade and systems model ($N = 552$). Numbers associated with single-headed arrows are standardized path coefficients; numbers associated with double-headed arrows are standardized covariance estimates; numbers associated with dependent variables are error variances or disturbance, the amount of variance not accounted for by paths in the model; numbers in parentheses are attenuation-corrected coefficients.

Figure 2.

Total effects, direct plus indirect effects, of cognitive domain predictors, child behavior difficulties, and maternal education on adolescent academic achievement in the final systems model ($N = 552$). Effect estimates are uncorrected standardized coefficients from the final model (Figure 1) and are in absolute values.

Table 1

Sociodemographic Characteristics of the Sample

	N	M(SD)
Child age at data collection		
Habituation (4 months)	552	3.83 (0.19)
Griffiths Mental Development Scales (18 months)	444	18.35 (0.35)
Wechsler Intelligence Scale for Children ^{UK} (8 years)	360	8.63 (0.19)
Key Stage 3 (14 years)	413	14.12 (0.37)
Child gender (% girls)	552	44.0%
Maternal age at child's birth (years)	552	28.90 (4.81)
Maternal education	525	
No qualifications	69	13.1%
Vocational school	54	10.3%
O level (secondary school completed)	192	36.6%
A level (college preparatory completed)	135	25.7%
College degree	75	14.3%

N represents number of available observations.

Table 2

Descriptive Statistics for Predictor and Outcome Variables

	N	M	SD
Habituation (s)	552	39.61	40.15
Griffiths Mental Development Scales General Developmental Quotient ^a	429	108.70	8.30
Wechsler Intelligence Scale for Children ^{UK} Full Scale Intelligence Quotient ^b	352	104.03	16.38
Key Stage 3 English ^c	391	46.95	16.29
Key Stage 3 Mathematics ^d	399	84.01	21.83
Key Stage 3 Science ^e	404	100.93	24.33
Infant Temperament Questionnaire ^f	511	0.00	0.90
Strengths and Difficulties Questionnaire ^g	285	5.90	5.84
Mother Parenting Score ^h	523	10.49	1.50
HOME Scale ⁱ	524	8.37	2.10

Note. Untransformed data. Analyses were conducted on transformed data.

^aThe GQ has $M = 100.1$, $SD = 12.8$ (Griffiths, 1984).

^bThe standard score has $M = 100$, $SD = 15$.

^cTotal score range: 0 – 100.

^dTotal score range: 0 – 150.

^eTotal score range: 0 – 180.

^fPrincipal axis factoring score.

^gTotal difficulties score range: 0 – 40.

^hTotal score range: 0 – 14.

ⁱTotal score range: 0 – 12.