Available online at www.sciencedirect.com

SCIENCE DIRECT®

Intelligence 32 (2004) 445–460

INTELLIGENCE

# Chaos in the home and socioeconomic status are associated with cognitive development in early childhood: Environmental mediators identified in a genetic design

Stephen A. Petrill[a,b,*], Alison Pike[c], Tom Price[d], Robert Plomin[e]

[a]Department of Biobehavioral Health, The Pennsylvania State University
[b]Center for Developmental and Health Genetics, The Pennsylvania State University, 101 Army Gardner House, University Park, PA 16802, United States
[c]Psychology Department, Sussex University, UK
[d]Wellcome Trust Center for Human Genetics, Oxford University, UK
[e]Social, Genetic, and Developmental Psychiatry Research Centre, Institute of Psychiatry, London

Received 4 August 2003; received in revised form 8 June 2004; accepted 25 June 2004

**Abstract**

The current study examined whether socioeconomic status (SES) and chaos in the home mediate the shared environmental variance associated with cognitive functioning simultaneously estimating genetic influences in a twin design. Verbal and nonverbal cognitive development were assessed at 3 and 4 years for identical and same-sex fraternal twin pairs participating in the Twins Early Development Study (TEDS). Verbal and nonverbal skills were measured using the McArthur Scales of Language Development (VERBAL) and the Parent Report of Children's Abilities (PARCA), respectively. SES and chaos were assessed via questionnaire. Results suggest that SES and CHAOS mediate an independent and significant, but modest, portion of the shared environment for VERBAL and PARCA at Ages 3 and 4.


*Keywords:* Chaos; Socioeconomic status; Genes

* Corresponding author. Center for Developmental and Health Genetics, The Pennsylvania State University, 101 Army Gardner House, University Park, PA 16802, United States. Tel.: +1 814 865 1717; fax: +1 814 863 4768.
*E-mail address:* sap27@psu.edu (S.A. Petrill).

0160-2896/$ - see front matter 
doi:10.1016/j.intell.2004.06.010

## 1. Introduction

For decades, socialization theorists have attempted to draw links between aspects of the environment and early cognitive development (see Wachs, 1996). By far, the most common approach has been to identify educational, behavioral, or societal environmental risk and protective factors that are correlated with cognitive development. These studies have been influential in demonstrating that family-level risk factors have a negative impact on children's cognitive functioning, independent of individual-level factors (e.g., Leventhal & Brooks-Gunn, 2000).

One factor is familial socioeconomic status (SES), which generally correlates between $r$=.30 and .40 with general cognitive ability (for a review, see Brody, 1992, or Jensen, 1998). In fact, this relationship is so robust cross culturally and across different types of measurement that it is standard practice to include SES as a covariate in studies of ability, rather than to focus on the effect of SES itself (e.g., Andersson, Sommerfelt, Sonnander, & Ahlsten, 1996; Martin, 1995).

The process by which SES impacts cognitive ability constitutes a central focus of inquiry in the developmental literature. Research has suggested that lower economic status is associated with less access to potential goods and services, as well as enhancing experiences, and greater exposure to harmful experiences and substances (e.g., Bradley & Whiteside-Mansell, 1997; Duncan & Brooks-Gunn, 1997; Huston, McLoyd, & Garcia Coll, 1994). As a result, researchers have attempted to examine the characteristics of the home environment that mediate the relationship between SES and cognitive outcomes. The HOME (Bradley & Caldwell, 1976, 1980; Caldwell & Bradley, 1978, 1984) is a set of tester-rated instruments that indexes multiple aspects of the home environment, which includes learning stimulation, parental responsiveness, spanking, as well as more physical aspects, such as the number of books on the shelves, cleanliness of the home, and crowding. Cherny (1994) suggested that this measure correlated $r$=.22 with general cognitive ability in childhood.

More recently, the degree of organization and calm in the household versus chaos has received attention (Matheny, Wachs, Ludwig, & Phillips, 1995). Using a parent report questionnaire, this construct has demonstrated modest to moderate links with children's general cognitive ability (Pike, Iervolino, Eley, Price, & Plomin, submitted for publication). This finding is particularly striking because the prediction from chaos held when controlling for SES, as well as eight additional environmental 'risk' variables such as parenting style and life events.

While the socialization literature has attempted to better understand individual differences in cognitive development by examining the taxonomy of the family environment, behavioral genetic research has attempted to better understand cognitive ability by estimating the relative importance of genetic, shared, and nonshared environmental influences. Numerous twin and adoption designs involving family members living together and apart have suggested that shared environmental influences approach zero by adolescence. However, in early childhood, the shared environment (e.g., growing up in the same home), along with genetics and the nonshared environment (and error), is important to cognitive ability in early childhood (Boomsma, 1993; McCartney, Harris, & Bernieri, 1990; McGue, Bouchard, Iacono, & Lykken, 1993; Plomin, 1986; Plomin, Fulker, Corley, & DeFries, 1997). Similarly, behavioral genetic research has suggested that the shared environment, as well as genetics, are important to the stability of cognitive skills in early childhood (see Petrill, 2002, for a review).

Until recently, socialization and behavioral genetic theories of development have employed very different methodologies. Socialization research has typically examined the environment in samples in which family members (parents and children) share genes as well as environments. Thus, these studies have confounded genetic and environmental influences (Rowe, 1994; Scarr, 1992). On the other hand, behavioral genetic studies have estimated the proportion of variance in cognitive ability influenced by genes, the shared (family level) environment, and nonshared (individual level) environment but have not attempted to identify specific genetic and environmental factors that constitute this variance.

There has been the beginning of a convergence between socialization and behavioral genetic designs in the developmental literature (Wachs, 1993). Socialization research has profited by being embedded in research designs that can take genetic influence into account in understanding environmental mechanisms. Behavioral genetic research has benefited by including specific measures of the environment (Plomin, 1994).

Thus, the goal of the present study is to examine the links between environmental markers and cognitive development in early childhood using the genetically sensitive Twins Early Development Study (TEDS). TEDS is a population-based study of all the twins born in England and Wales from 1994 to 1996 (see Trouton, Spinath, & Plomin, 2002). We chose to focus our attention on two factors linked to general cognitive ability in the extant literature, as well as within the TEDS sample (Pike et al., submitted for publication): SES and the level of chaos versus organization in the home environment.

In particular, we examined three issues with respect to the relationship between SES, chaos in the home, and general cognitive ability in early childhood. First, after controlling for genetic influences on cognitive ability, we examined the extent to which SES and chaos accounted for the shared environmental variance in cognitive ability at Ages 3 and 4. Second, we examined the extent to which SES and chaos influenced the stability in cognitive skills from Ages 3 to 4, after controlling for genetic influences on the stability of cognitive skills. Third, we examined whether chaos constitutes an independent source of shared environmental variance, or whether it is completely explained by SES.

## 2. Method

### 2.1. Participants

Twins are participants in the Twins' Early Development Study (TEDS), an ongoing longitudinal study examining all twins born in England and Wales in 1994, 1995, and 1996. Following a screen for infant mortality, 16,810 families with twins were identified by the Office for National Statistics (ONS). When the children were 1 year old, a letter was sent via mail to each of these families briefly explaining the project, along with a return-addressed postcard of interest. Those parents who responded were then mailed a first contact booklet explaining the project in greater detail, as well as a questionnaire requesting background demographic information. Zygosity was assessed through a parent questionnaire measuring the twins' physical similarity derived from Goldsmith (1991) (Price, Petrill, Dale & Plomin, submitted for publication). Unclear cases were resolved through a DNA screening procedure. For the purposes of the current study, we excluded 554 pairs, in which at least one twin had a specific medical syndrome, were extreme outliers for perinatal problems (e.g., extreme low birth weight), or where no gender information was available.

Additional questionnaire booklets were sent shortly before the twins' second, third, and fourth birthdays for the 1994 and 1995 cohorts. Due to budgetary constraints, the 1996 cohort was assessed at first contact and at Age 4. Of the 12,346 families who returned the first contact booklet and were not excluded, 5790 families also returned the 2-year booklet, 5657 families returned the 3-year booklet, and

6706 families returned the 4-year booklet. The families participating in this study are representative of the general population, as indexed by zygosity, education, and occupational status (see Dale et al., 1998). Opposite-sex DZ pairs were also excluded from this study. Pairwise deletion yielded 3915 MZ and 3866 same-sex DZ pairs.

### 2.2. Measures

#### 2.2.1. Socioeconomic status

All demographic information was obtained from the first contact booklet. An index of SES was created based on a factor analysis of the fathers' highest educational level and occupational status and the mothers' highest educational level and occupational status, and age of mother at birth of eldest child. Using principal components analysis, a single-factor solution yielded an eigenvalue of 2.51, accounting for 50% of the variance. Based on these results, a single composite was created. These five variables were standardized and then summed using unit weights.

#### 2.2.2. Chaos

The degree of chaos in the home was assessed within both the 3- and 4-year booklets using the short-form version of the Confusion, Hubbub, and Order Scale (CHAOS: Matheny et al., 1995). The scale consists of six items rated on a five-point scale (1=*definitely untrue*, 5=*definitely true*) about the levels of chaos in the home. The sample items include "You can't hear yourself think in our home" and "We are usually able to stay on top of things" (reversed). A total chaos score was generated at Ages 3 and 4 by summing the items (following reverse scoring so that high values=high chaos). The items possessed acceptable internal consistency, as measured by Cronbach's alpha ($\alpha$=.63).

#### 2.2.3. Cognitive development

The overarching goal of TEDS is to examine the links between verbal and nonverbal skills and behavior problems in early childhood. Given the large sample size and geographical distribution of the TEDS sample, it was necessary to develop parent-administered measures of verbal and nonverbal cognitive performance. The current study examines verbal and nonverbal cognitive skills assessed longitudinally at Ages 3 and 4. Verbal skills were measured using two subscales, Expressive Vocabulary and Grammatical Complexity. These measures were developed for TEDS as an extension of the MacArthur Communication Development Inventory (MCDI: Fenson et al., 1994), which correlated $r$=.73 with standardized tester-administered measure of expressive vocabulary with children aged 2.0 years (reviewed in Fenson et al., 1994) and $r$=.85 with a sample of language-impaired children at 3.0 years (Thal, O'Hanlon, Clemmons, & Fralin, 1999).

The MCDI was shortened and anglicised for TEDS (Dale et al., 1998). In a validation sample of 107 children (all twins or triplets), we found a correlation of $r$=.58 between expressive vocabulary and the language subscale of the Bayley Scales of Infant Development-II Language scale at 2 years (Saudino et al., 1998). Moreover, in another study of 85 British children at 2.8–3.4 years, the correlations between the vocabulary measure at 3.0, administered by mail, and the McCarthy Scales of Children's Abilities Verbal Score, administered by testers in the home, were $r$=.68 and .48 for first- and second-born twins, respectively (birth order within the twin pair; Oliver et al., 2002). Grammatical Complexity, also drawn from the MCDI, examines the whether and how children are combining words. Grammatical Complexity has been shown to correlate significantly with Vocabulary, not only within age but also across measurement occasions (Dale, Price, Bishop, & Plomin, 2003; Dionne, Dale, Boivin, & Plomin, 2003). Furthermore, Dionne et al. (2003) demonstrated that genetic influences were largely stable longitudinally. The total VERBAL scores at Ages 3 and 4 were calculated by standardizing the Vocabulary and Grammatical Complexity subtests then summing these subtests within each age. Vocabulary correlated $r$=.53 and .44 with Grammatical Complexity at Ages 3 and 4, respectively, in the current study.

The success of the parent report of language prompted an interest in the development of a parent-based measure of nonverbal cognitive skills, the Parent Report of Children's Abilities (PARCA; Saudino et al., 1998). The PARCA is a two-part measure in which parents fill in a questionnaire about their children's cognitive abilities and administer an hour-long battery of cognitive tests based upon age-appropriate developments of the match-to-sample and design-drawing tasks, supplemented by an odd-man-out task. The intercorrelation among PARCA subtests was best fitted by a single phenotypic factor, influenced both by genes and the shared environment (Petrill, Saudino, Wilkerson, & Plomin, 2001). The total PARCA score, derived from both the parent report and the parent-administered components in 2-year-old twins, was found to predict performance on the Mental Development Index (MDI) of the Bayley Scales of Infant Development-II (Bayley, 1993; $r$=.51, $P$<.001). Year 3 PARCA scores were compared with in-home testing on the McCarthy Scales of Children's Development and yielded a correlation of $r$=.46 (Oliver et al., 2002). In addition, a McCarthy nonverbal composite, calculated from the quantitative and perceptual performance scales, correlated $r$=.54 with the PARCA. Total scores at Ages 3 and 4 were calculated by standardizing and summing all subtests within each age.

The analysis focused on the extent to which SES and CHAOS mediate a portion of the shared environmental variance predicting VERBAL and PARCA at Ages 3 and 4 while simultaneously estimating components of the nonshared environment and genetics.

#### *2.2.4. Phenotypic analyses*

Means, standard deviations, and Pearson correlations were analyzed to provide a general picture of the relationship among SES, CHAOS, and cognitive performance at Ages 3 and 4.

#### *2.2.5. Univariate genetic analyses*

Typically, genetic, shared environmental, and nonshared environmental influences are estimated by comparing the covariance among family members of different genetic relatedness (Plomin, DeFries, McClearn, & McGuffin, 2001). In the case of twins, higher identical twin covariance on verbal and nonverbal cognitive skills relative to fraternal twins implies genetic influences. To the extent that the covariance on cognitive skills for identical twins is similar in magnitude to that for fraternal twins, then shared environmental influences are implied. To the extent that covariance among identical twins is less than 1.0, nonshared environmental influences (including error) are estimated.

In addition, the current study also includes three "measured" environmental variables, SES, chaos at Age 3 (CHAOS3), and chaos at Age 4 (CHAOS4). Because these measures are family specific (the entire family gets a score for each variable), they are, by definition, shared environmental variables. The main issue is whether these identified measures account for a significant portion of the shared environmental variance in cognitive performance at Ages 3 and 4 while simultaneously estimating genetic, shared, and nonshared environmental effects.

To address this question, a model was developed based on Neale and Martin (1989) and is analogous to models employed to estimate the effect of DNA markers upon an outcome variable while simultaneously estimating background genetic or familial resemblance. The present model is an extension of a similar model applied to TEDS data to assess the effects of neighborhoods on adjustment (Caspi, Taylor, Moffitt, & Plomin, 2000). This model estimates the proportion of variance that an identified measure (e.g., SES) predicts cognitive ability while simultaneously estimating genetic (A), shared environmental (C), and nonshared (E) environmental factors (see Fig. 1). In this model, twin resemblance in VERBAL3 is influenced by a common set of genetic, shared, and nonshared environmental influences (A, C, and E, respectively). Additionally, twin resemblance is also influenced by a measured environmental variable (SES), which, for purposes of model identification, is equated for both twins. Because each family member receives the same SES and CHAOS value, these measured environmental influences will account for shared environmental influences on VERBAL. PARCA and Verbal skills were examined at Ages 3 and 4 (four outcome variables total) across two measures of the identified environment (SES and CHAOS), yielding eight separate univariate analyses: SES and VERBAL at Age 3; SES and VERBAL at Age 4; CHAOS at Age 3 and VERBAL at Age 3; CHAOS at 4 and VERBAL at Age 4; SES and PARCA at Age 3; SES and PARCA at Age 4; CHAOS at Age 3 and PARCA at Age 3; and CHAOS at Age 4 and PARCA at Age 4. Ninety-five percent (95%) confidence intervals were used to test the significance of the A, C, E and measured environmental (e.g., SES) variance components. All analyses were conducted using Mx (Neale, Boker, Xie, & Maes, 1999).

### *2.2.6. Multivariate analyses*

The univariate models described above are useful in that they describe the proportion of variance in VERBAL and PARCA that is accounted for by individual measured environmental variables. However, these models do not elucidate how these identified environmental measures are associated with one another. Additionally, univariate models do not describe how identified measures of the environment influence the stability of cognitive ability at Ages 3 and 4. Thus, a multivariate extension

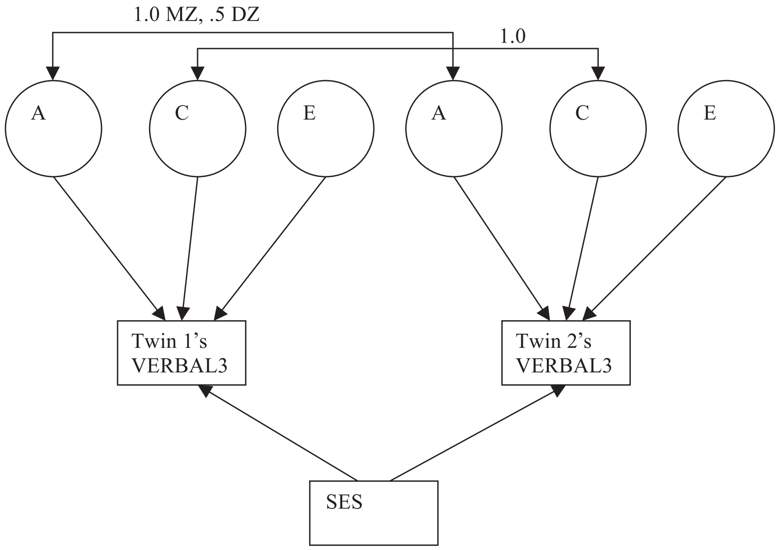


Fig. 1. Univariate mediation model estimating genetic, shared environmental, nonshared environmental, and identified variance in VERBAL.

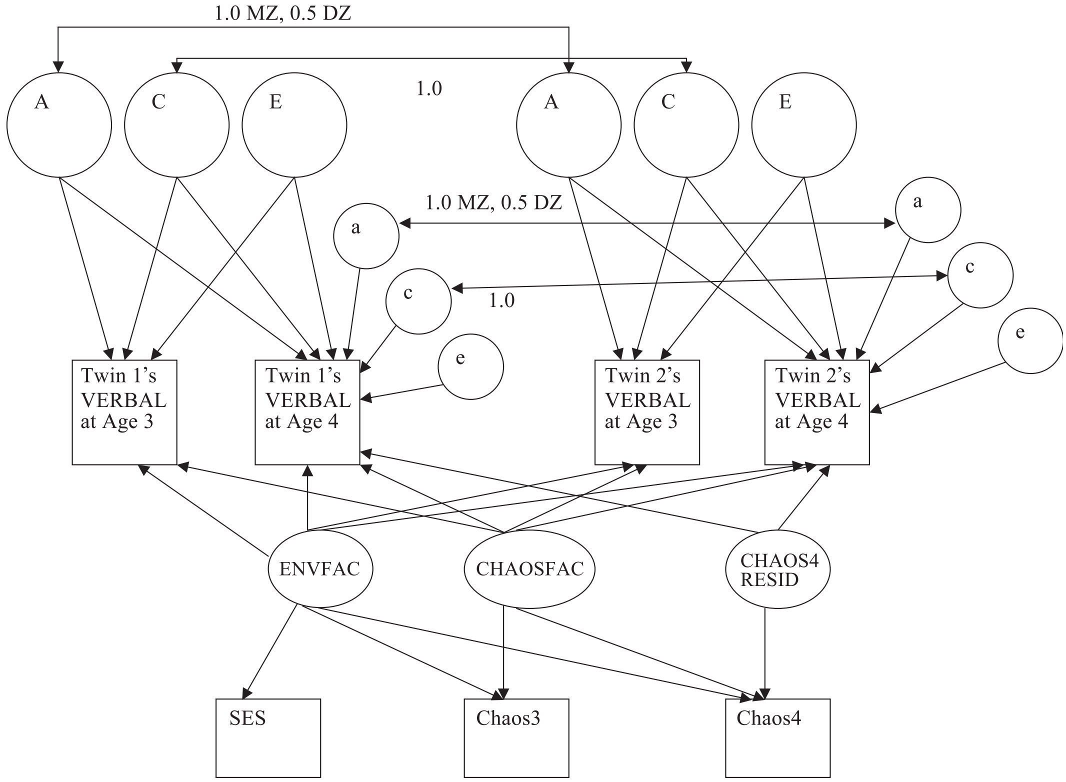


Fig. 2. Multivariate mediation model estimating genetic, shared environmental, nonshared environmental, and identified variance in VERBAL at Ages 3 and 4.

of the univariate model was developed. This model was fit separately for the VERBAL and PARCA scales.[1]

Using VERBAL as an example in Fig. 2, the covariance among VERBAL scores at Ages 3 and 4 is influenced by a common set of genetic, shared, and nonshared environmental influences (A, C, and E, respectively). VERBAL at Age 4 is influenced by a set of specific genetic, shared, and nonshared effects ($a$, $c$, and $e$). To the extent that the correlation between VERBAL at Ages 3 and 4 is influenced by genetic factors, the pathways from A to VERBAL 3 and VERBAL 4 will be significant. To the extent that the discrepancy between VERBAL at Ages 3 and 4 is influenced by different genetic factors, the pathway from $a$ to VERBAL at Age 4 will be significant. The same logic applies for the shared (C, $c$) and nonshared (E, $e$) factors.

Additionally, the covariance among the VERBAL at Ages 3 and 4 is also influenced by three factors based upon the "measured" variables of SES, Chaos at age 3 and Chaos at age 4. These three measured variables were set to load on three environmental factors. The first factor (ENVFAC)

[1] Our focus is on a multivariate, longitudinal analysis of the environmental measures as they relate separately to VERBAL and to PARCA. Although not presented in this paper, we also conducted more complex multivariate analyses that included both VERBAL and PARCA in the same model, thus examining the covariation between VERBAL and PARCA. These results, available from the first author, were nearly identical to the more straightforward model-fitting results presented in the current study.

measures the covariance of SES, CHAOS3, and CHAOS4. The second factor (CHAOSFAC) measures the residual covariance of CHAOS3 and CHAOS4 that is independent from SES. Finally, the third factor (CHAOS4RESID) accounts for the residual variance in chaos at Age 4 that is independent from SES and CHAOS at age 3.

In this way, it is possible to estimate both the covariance among these identified measures of the environment, their independence, and their relationship with verbal skills at Ages 3 and 4. If SES, CHAOS3, and CHAOS4 are influenced by a unidimensional and longitudinally stable "quality of the environment," then ENVFAC should covary significantly with VERBAL 3 and VERBAL 4 while the CHAOSFAC and CHAOS4RESID factors should not. If chaos predicts variance in VERBAL 3 and VERBAL 4, independent from SES, then CHAOSFAC and CHAOS4RESID will be significantly associated with the VERBAL measures. Furthermore, if chaos in the home is stable from Ages 3 to 4, then CHAOSFAC, because it indexes the covariance between chaos at Ages 3 and 4, will be significant, and CHAOS4RESID will not. If chaos is age specific, then both CHAOSFAC and CHAOS4RESID will be significantly associated with verbal skills. Following the examination of VERBAL skills, analogous models were conducted using the PARCA.

## 3. Results

### 3.1. Phenotypic analyses

Table 1 presents the means and standard deviations for SES, CHAOS3, CHAOS4, VERBAL3, VERBAL4, PARCA3, and PARCA4 by gender and zygosity. The means and standard deviations are roughly similar across all comparisons, although males are slightly higher in CHAOS, but lower in VERBAL and PARCA, than females are. Correlations between SES, CHAOS3, CHAOS4, VERBAL3, VERBAL4, PARCA3, and PARCA4 are presented in Table 2. SES is positively associated with VERBAL and PARCA, while CHAOS is negatively correlated with VERBAL and PARCA. SES is negatively associated with CHAOS. Furthermore, CHAOS3 is highly correlated with CHAOS4 (*r*=.69), VERBAL3 is highly correlated with VERBAL4 (*r*=.66), and PARCA3 is likewise highly correlated with PARCA4 (*r*=.61).

Table 1
Means and standard deviations for SES, CHAOS, and PARCA by gender and zygosity

| Variable | MZ Male | | | DZ Male | | | MZ Female | | | DZ Female | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | S.D. | *n* | Mean | S.D. | *n* | Mean | S.D. | *n* | Mean | S.D. | *n* |
| SES | −0.09 | 0.71 | 3564 | 0.04 | 0.73 | 3734 | −0.05 | 0.72 | 3788 | 0.04 | 0.74 | 3636 |
| CHAOS3 | 0.06 | 1.58 | 1786 | 0.11 | 1.66 | 1882 | −0.06 | 1.57 | 2046 | −0.11 | 1.64 | 1788 |
| CHAOS4 | 0.17 | 1.61 | 2052 | 0.17 | 1.62 | 2174 | −0.07 | 1.64 | 2392 | −0.16 | 1.67 | 2202 |
| VERBAL3 | −0.40 | 1.80 | 1558 | −0.14 | 1.69 | 1667 | 0.16 | 1.71 | 1836 | 0.38 | 1.60 | 1595 |
| VERBAL4 | −0.23 | 1.81 | 1982 | −0.09 | 1.74 | 2107 | −0.02 | 1.69 | 2305 | 0.24 | 1.51 | 2148 |
| PARCA3 | −0.13 | 1.00 | 1748 | −0.15 | 0.99 | 1838 | 0.14 | 0.97 | 2022 | 0.21 | 0.94 | 1774 |
| PARCA4 | −0.18 | 1.04 | 2001 | −0.10 | 1.00 | 2139 | 0.05 | 0.94 | 2349 | 0.16 | 0.91 | 2177 |

The number of individuals using all available data from the 1994, 1995, and 1996 cohorts is referred to by *n*.

Table 2
Phenotypic correlations among socioeconomic status (SES), chaos in the home (CHAOS), and cognitive ability (PARCA) at Ages 3 and 4

| Variable | SES | CHAOS3 | CHAOS4 | VERB3 | VERB4 | PARCA3 | PARCA4 |
|---|---|---|---|---|---|---|---|
| SES | 1.00 | | | | | | |
| (*n*) | 14722 | | | | | | |
| CHAOS3 | −.28 | 1.00 | | | | | |
| (*n*) | 6946 | 7502 | | | | | |
| CHAOS4 | −.28 | .69 | 1.00 | | | | |
| (*n*) | 8170 | 5728 | 8820 | | | | |
| VERBAL3 | .18 | −.20 | −.20 | 1.00 | | | |
| (*n*) | 6179 | 6612 | 5136 | 6656 | | | |
| VERBAL4 | .19 | −.17 | −.18 | .66 | 1.00 | | |
| (*n*) | 7923 | 5540 | 8430 | 5000 | 8542 | | |
| PARCA3 | .12 | −.22 | −.21 | .48 | .42 | 1.00 | |
| (*n*) | 6837 | 7323 | 5654 | 6950 | 5484 | 7382 | |
| PARCA4 | .15 | −.21 | −.22 | .44 | .45 | .61 | 1.00 |
| (*n*) | 8027 | 5577 | 8544 | 5017 | 8377 | 5529 | 8666 |

All correlations are significant $P<.001$.
The individuals using all available data from the 1994, 1995, and 1996 cohorts are referred to by *n*.

### 3.2. Univariate genetic analyses

As described in the Participants section, the 1996 cohort was not assessed at Year 3. Although listwise deletion is conservative in that it employs only cases with complete data, this procedure effectively deletes the entire 1996 cohort from the genetic analyses ($n$=3793). Thus, using the model in Fig. 1, the relationship between SES, CHAOS, and cognitive skills was examined using raw data so that data from the 1996 cohort could be included. Univariate analyses suggest modest heritability and substantial shared environment for both VERBAL and PARCA at Years 3 and 4, results similar to those reported previously in TEDS, as well as in other studies of cognitive development in early childhood (Price, Eley

Table 3
Univariate model fitting results

| Variable | $h^2$ | $c^2$ | $e^2$ | SES$^2$ | CHAOS$^2$ | −2ll | *df* |
|---|---|---|---|---|---|---|---|
| VERBAL 3 | | | | | | | |
| SES mediation | .31* | .58* | .08* | .03* | | 38025.24 | 14006 |
| CHAOS mediation | .31* | .57* | .08* | | .04* | 36011.53 | 10396 |
| VERBAL 4 | | | | | | | |
| SES mediation | .26* | .58* | .12* | .04* | | 44650.11 | 15892 |
| CHAOS mediation | .26* | .58* | .12* | | .03* | 45317.64 | 12941 |
| PARCA3 | | | | | | | |
| SES mediation | .26* | .58* | .15* | .01* | | 32983.72 | 14627 |
| CHAOS mediation | .25* | .55* | .15* | | .05* | 30861.23 | 11017 |
| PARCA4 | | | | | | | |
| SES mediation | .24* | .57* | .17* | .02* | | 36003.99 | 15874 |
| CHAOS mediation | .24* | .54* | .17* | | .05* | 36537.32 | 12923 |

Using all available data from 1994, 1995, and 1996 cohorts, $n$=3915 MZ and $n$=3866 same-sex DZ pairs.
* $P<.05$ using 95% confidence intervals.

et al., 2000; Price, Petrill, Dale, & Plomin, submitted for publication). Shared environment is divided into variance accounted for by SES and CHAOS, and unidentified shared environmental influences ($c^2$). SES and CHAOS are associated with a statistically significant proportion of the variance in VERBAL and PARCA at Ages 3 and 4, beyond that accounted for by genetic, nonshared environmental, and unidentified shared environmental influences (see Table 3). These measured environmental variables accounted for between 1% and 5% of the total variance, and 54–61% of the total variance was explained by unmeasured shared environmental influences.

### 3.3. Multivariate genetic analyses

Univariate analyses, although informative, examined neither the covariance among cognitive ability from Ages 3 to 4 nor the relationship among measured environmental variables. To address these issues, the model presented in Fig. 2 was employed using raw data. This model was fit to VERBAL then PARCA measures in separate analyses (see Table 4).

By comparing the fit of submodels to the full model, it is possible to test whether SES, CHAOS3, and CHAOS4 account for a significant proportion of the variance in VERBAL and PARCA at Ages 3 and 4. Goodness-of-fit was assessed using the likelihood ratio test (Δ−2LL) and the Bayesian Information Criterion Change (ΔBIC; Raftery, 1995) statistics. The Δ−2LL statistic tests whether the change in log-likelihood of a submodel versus the full model is significant using a chi-square difference test. The ΔBIC statistic was the preferred index of fit because parsimony is not negatively influenced by large sample sizes. The BIC statistic is calculated as

$$\Delta\text{BIC} = \Delta - 2\ \text{LL} - \Delta df \ln(n)$$

where Δ−2LL is the difference in log likelihood between the full model and the submodel, Δ*df* is the change in the number of degrees of freedom, and *n* is the sample size. Differences of more than 10 indicates a significant decrease in model fit.

Table 4
Model fitting results examining SES, CHAOS3, and CHAOS4 mediation of the shared environment: VERBAL and PARCA

| Model | −2ll | *df* | Δ−2ll | Δ*df* | ΔBIC |
|---|---|---|---|---|---|
| *VERBAL* | | | | | |
| Full | 93182.692 | 30686 | | | |
| Drop environmental factor | 93386.524 | 30688 | 203.832* | 2 | 188.558* |
| Drop CHAOS | 93306.761 | 30689 | 124.069* | 3 | 101.158* |
| Drop correlation between common CHAOS factor and PARCA4 | 93255.238 | 30687 | 72.546* | 1 | 64.909* |
| DROP CHAOS4 residual | 93187.771 | 30687 | 3.079 | 1 | −4.558 |
| *PARCA* | | | | | |
| Full | 79571.57 | 31289 | | | |
| Drop environmental factor | 79699.75 | 31291 | 128.18* | 2 | 112.6* |
| Drop CHAOS | 79805.65 | 31292 | 234.08* | 3 | 210.7* |
| Drop Correlation between common CHAOS factor and PARCA4 | 79721.91 | 31290 | 150.34* | 1 | 142.5* |
| DROP CHAOS4 residual | 79584.63 | 31290 | 13.06* | 1 | 5.3 |

Using all available data from the 1994, 1995, and 1996 cohorts, *n*=3915 MZ and *n*=3866 same-sex DZ pairs.
* Significant decrease in model fit.

Four submodels were fit to test the significance of the identified environmental influences for VERBAL and PARCA. The first, Drop Environmental Factor, set the direct effect of the common factor of ENVFAC to zero (see Fig. 2). If this submodel fit significantly worse than the full model does, as tested by a $\Delta -2LL$ and $\Delta BIC$ tests, then it was assumed that the covariance among SES and CHAOS was a significant predictor of VERBAL and/or PARCA at Ages 3 and 4. The second submodel dropped the direct effects of CHAOSFAC and CHAOS4RESID to test whether chaos predicted significant variance in VERBAL and/or PARCA, independent from SES. The third submodel tested whether variance associated with CHAOSFAC was associated with VERBAL and/or PARCA at Age 4. Finally, the fourth submodel (DROP CHAOS4 Residual) tested whether the variance in CHAOS4 was associated with VERBAL and/or PARCA, independent from SES and CHAOS3. These four submodels were estimated for VERBAL, then again for PARCA, in separate analyses.

Examining the results for VERBAL in Table 4, results suggest that ENVFAC and CHAOSFAC were both significant mediators of the shared environmental influences associated with VERBAL at Ages 3 and 4. In contrast, CHAOS4 Residual was not a significant mediator of VERBAL skills at Age 4. A similar pattern was found when examining the PARCA (see Table 4). ENVFAC and CHAOSFAC were important to the fit of the model. However, results were mixed for CHAOS4RESID. The log-likelihood difference ($\Delta -2LL=13.06$, $\Delta df=1$) suggested that CHAOS4RESID was significant while the BIC test ($\Delta BIC=5.3$, $\Delta df=1$) did not.

Univariate estimates derived from the full multivariate models for VERBAL and PARCA are presented in Table 5. When simultaneously estimating the genetic, nonshared environmental, and residual shared environmental variance, ENVFAC, or the latent variable representing the common variance among SES and CHAOS, accounts for 5% of the shared environmental variance [.03/(.56+.03+.03)] and 3% of the total variance in Verbal at Age 3 and 6% of the shared environmental

Table 5
Heritability, shared, nonshared, and identified environmental influence in VERBAL and PARCA at Ages 3 and 4 estimated from multivariate models

| Estimate | Age 3 | Age 4 |
|---|---|---|
| *VERBAL* | | |
| $h^2$ | .30 | .27 |
| $c^2$ | .56 | .56 |
| $e^2$ | .08 | .12 |
| $ENVFAC^2$ | .03 | .04 |
| $CHAOSFAC^2$ | .03 | .02 |
| $CHAOS4RESID^2$ | xx | .00 |
| (Total measured environment$^2$) | (.06) | (.06) |
| | | |
| *PARCA* | | |
| $h^2$ | .25 | .24 |
| $c^2$ | .55 | .53 |
| $e^2$ | .15 | .17 |
| $ENVFAC^2$ | .01 | .02 |
| $CHOASFAC^2$ | .04 | .03 |
| $CHAOS4RESID^2$ | xx | .01 |
| (Total measured environment$^2$) | (.05) | (.06) |

Results for VERBAL and PARCA estimated in separate analyses.

variance and 4% of the total variance in Verbal at Age 4. CHAOSFAC, or the residual covariance among CHAOS3 and CHAOS4, independent from SES, accounts for 5% of the shared environmental variance and 3% of the total variance in Verbal at Age 3 and 3% of the shared environmental variance and 2% of the total in Verbal at Age 4. As expected from the model fitting results in Table 4, the effects CHAOS4, independent from SES and CHAOS3 (CHAOS4RESID), approached zero. Taken together, the measured environmental variables accounted for 10% of the shared environmental variance and 6% of the total variance in VERBAL3 and VERBAL4. A similar pattern was found for the PARCA. The measured environmental variables accounted for 8% (.05/.60) of the shared environmental variance and 5% of the total variance at Age 3 and 10% of the shared environmental and 6% of the total variance at Age 4.

The covariance of cognitive performance at Years 3 and 4 was also examined using the model presented in Fig. 2 (see Table 6). The Cholesky structure presented in Fig. 2 makes it possible to decompose the correlation between verbal skills at Ages 3 and 4 into genetic, shared, environment, nonshared environment, and identified environmental pathways. For example, the genetic covariance between verbal skills at Ages 3 and 4 is estimated by the product of the pathways from Verbal at Age 3 to A then to Verbal at Age 4. The same logic applies for C, E, and identified environmental factors. Using this approach, the estimated phenotypic correlation between verbal skills at Ages 3 and 4 was .65. ENVFAC, or the covariance among SES, CHAOS3, and CHAOS4, accounted for 5% (.03) of this correlation. The residual covariance between CHAOS3 and CHAOS4, independent from SES (CHAOSFAC), accounted for 3% (.02) of the correlation between VERBAL3 and VERBAL4. Taken together, the measured environmental variables accounted for 8% (.05) of this correlation. Residual shared environment accounted for 58% (.38), genetics accounted for 32% (.21), and the nonshared environment account for 2% (.01) of the correlation between VERBAL3 and VERBAL4. A similar pattern of results was found when examining the relationship between PARCA at Ages 3 and 4.

Table 6
Genetic, shared environment, nonshared environmental, and identified environmental correlations between VERBAL and PARCA at Ages 3 and 4

| Estimate | Correlation | Proportion (%) |
|---|---|---|
| *VERBAL 3 and VERBAL 4* | | |
| Genetic | .21 | 32 |
| Shared environment | .38 | 58 |
| Nonshared environment | .01 | 2 |
| ENVFAC | .03 | 5 |
| CHAOSFAC | .02 | 3 |
| (Total measured environment) | (.05) | (8) |
| Total estimated correlation | .65 | 100 |
| *PARCA3 and PARCA4* | | |
| Genetic | .18 | 29 |
| Shared environment | .37 | 60 |
| Nonshared environment | .01 | 1 |
| ENVFAC | .02 | 3 |
| CHAOSFAC | .04 | 7 |
| (Total measured environment) | (.06) | (10) |
| Total estimated correlation | .62 | 100 |

Results for VERBAL and PARCA were estimated in separate analyses.

## 4. Discussion

The present study explored the roles of SES and chaos within the home environment for young children's cognitive abilities within a genetically sensitive design. These factors were shown to partially mediate the shared environmental influences for verbal and nonverbal measures of cognitive ability at Ages 3 and 4. Furthermore, SES and chaos significantly mediated the stability of verbal and nonverbal cognitive skills from Ages 3 to 4. Finally, chaos within the home was a significant mediator, even when controlling for SES.

The association of SES with general cognitive ability is a well-established and robust finding (Brody, 1992). It is perhaps, then, not surprising to discover that SES is a significant mediator of the shared environmental influences on young children's cognitive abilities. We also were impressed by the fact that general chaos (vs. organization) of the home environment also provided significant, and longitudinally stable, shared environmental mediation in verbal and nonverbal cognitive skills. This effect of growing up in a calm, well-organized household, which, importantly, is not necessarily synonymous with higher SES, demonstrates that the more proximal home environment provided by parents has important consequences for children's development. Perhaps, a child growing up in a well-ordered home is able to explore and interact in that environment in ways that stimulate cognitive advances, or it may be that a chaotic home environment is a marker for parenting stress that results in parent–child interactions lacking in adequate verbalization, scaffolding, and nurturing of the child's cognitive development. Furthermore, chaos may also be a marker for parental and child personality characteristics or other family factors, such as family size, that may influence intelligence. Although the mechanism of the relationship between chaos and cognitive skills is unclear, we have shown in the current study that these influences are independent from those associated with SES and that the effects of chaos are stable longitudinally.

Although significant, these mediation effects are modest in magnitude. In particular, SES generally correlates with general cognitive ability in the $r$=.30 to 40 range (Jensen, 1998) but correlates $r$=.12 to .19 with our measures of cognitive ability. Given the representativeness of the TEDS sample, it is unlikely that restriction in range of the family environment is resulting in lowered correlations. Instead, a necessary consequence of the large number of participants in TEDS is that measurement is focused on breadth rather than depth and the data were collected via postal questionnaires and parent-administered cognitive tasks. This measurement strategy may have resulted in a higher proportion of twin- or measurement-specific shared environmental variance (as suggested by Koeppen-Schomerus, Spinath, & Plomin, 2003), resulting in attenuated results for SES, chaos, and cognitive outcomes. Related to this issue, heritability estimates for verbal and nonverbal cognitive skills were lower in the current study than has been found in the extant literature. This result may also be a consequence of using parent report, which may inflate overall twin resemblance. Another limitation of the current study was that a limited set of environmental markers was employed in the current study. Finally, opposite-sex pairs were excluded from the analysis. Although this prevented us from examining sex-limitation effects, we were most concerned with initial question of whether SES and CHAOS mediated the shared environment.

We have shown that SES and chaos partially mediate the shared environmental effects on verbal and nonverbal cognitive ability for young children, even after controlling for genetic differences in cognitive ability. While by no means exhaustive, SES and chaos yielded highly similar results across verbal and nonverbal measures of cognitive ability. SES and chaos explained roughly 5% of the total variance in verbal and nonverbal skills at Ages 3 and 4, even after controlling for the genetic influences upon verbal and nonverbal cognitive skills. Furthermore, these factors accounted for approximately 10% of the shared environmental influences at Ages 3 and 4. Finally, chaos and SES together accounted for around 10% of the phenotypic correlation among verbal and nonverbal cognitive skills across age. These findings will be bolstered by replication with more in-depth measures and tester-administered cognitive ability tests. A subsample of TEDS families participate in at-home in-depth assessments at 4 years that will provide important replication of this pattern of results when all three cohorts have been completed.

However, it is also possible that passive genotype–environment (G–E) correlation may be masked as shared environmental effects in our twin design. Passive G–E correlations refer to the fact that parents provide both genes and environmental experiences for their children, and that these two factors may be correlated with one another. In the present context, parents provided familial SES, as well as homes, that run along the continuum from very well ordered to extremely chaotic. These environments may be influenced by parental genotype. Previous adoption studies have suggested that passive G–E correlation is negligible in general cognitive ability in early childhood (Plomin & DeFries, 1985), hence, it is likely that our results reflect shared environment rather than passive G–E correlation. However, we cannot empirically rule out the presence of passive gene–environment correlation in our results. Only in adoptive families is the link between parental genotype and parental environment provisions severed, thereby enabling the size of this effect to be estimated (see Plomin et al., 2001, for details).

These results highlight the need to conduct environmentally informative research using genetically sensitive designs. The extant behavioral genetic literature has already shown that the environment functions differently than hypothesized by most developmentalists. The transactional interplay of genetic and environmental influences, and consequent ubiquity of gene–environment correlations and interactions, suggests that behavioral genetic experiments incorporating measured environments will play a vital part in understanding the processes underlying cognitive development (Rutter & Silberg, 2002). For example, the shared environmental etiology of cognitive skills drops to zero by adolescence, but this does not mean that the environment is unimportant after adolescence, nor does it mean that environmental experiences have to be subsumed under the nonshared environment. Instead, it may be the case that as children become older, they exhibit more control over their environments (Scarr & McCartney, 1983). Identical twins may be more likely to come into contact with more similar environments than fraternal twins do because of their greater genetic similarity, and these environmental experiences, in turn, may make identical twins more similar. These kinds of gene–environment transaction are estimated as heritability using the sibling-only twin design employed by the majority of behavioral genetic studies. Beyond merely estimating components of variance, we know very little about what these environmental influences are, or how they are influenced by gene–environment effects. Massive monetary investment has gone into the search for specific genes in recent years. Far less attention has been paid towards identifying environmental factors and how they operate independently and in concert with child- and parent-driven genetic effects. While we have not addressed potential shifts between shared environment and gene–environment correlation between childhood and adolescence, the present study contributes to this endeavor in that we have identified two sources of shared environmental variance that influence cognitive skills in early childhood. Finally, we argue that real advances in understanding the complexities of children's development will be possible when the specification of genes, environmental factors, and interactive effects of the two are integrated within single research agendas.

## Acknowledgements

TEDS is supported by a program grant from the Medical Research Council of the United Kingdom. The authors wish to thank Andrew McMillan for his data management expertise as well as the parents of the twins and all staff members for making this study possible.

## References

Andersson, H. W., Sommerfelt, K., Sonnander, K., & Ahlsten, G. (1996). Maternal child rearing attitudes, IQ, and socioeconomic status as related to cognitive abilities of five-year-old children. *Psychological Reports*, *79*, 3–14.

Boomsma, D. I. (1993). Current status and future prospects in twin studies of the development of cognitive abilities: Infancy to old age. In T. J. Bouchard, Jr., & P. Propping (Eds.), *Twins as a tool of behavioral genetics* (pp. 67–82). Chichester, UK: Wiley.

Bayley, N. (1993). *Bayley scales of infant development*. New York: The Psychological.

Bradley, R., & Caldwell, B. (1976). Early home environment and changes in mental test performance from 6 to 36 months. *Developmental Psychology*, *12*, 93–97.

Bradley, R., & Caldwell, B. (1980). Home environment, cognitive competence, and IQ among males and females. *Child Development*, *51*, 1140–1148.

Bradley, R., & Whiteside-Mansell, L. (1997). Children in poverty. In R. T. Ammerman, & M. Hersen (Eds.), *Handbook of prevention and treatment with children and adolescents* (pp. 13–58). New York: Wiley.

Brody, N. (1992). Intelligence. (2nd ed.). New York: Academic Press.

Caldwell, B., & Bradley, R. (1978). *Home observation for measurement of the environment*. Little Rock, AR: University of Arkansas.

Caldwell, B., & Bradley, R. (1984). *Home observation for measurement of the environment*. Little Rock, AR: University of Arkansas at Little Rock.

Caspi, A., Taylor, A., Moffitt, T. E., & Plomin, R. (2000). Neighborhood deprivation affects children's mental health: Environmental risks identified in a genetic design. *Psychological Science*, *11*(4), 338–342.

Cherny, S. S. (1994). Home environmental influences on general cognitive ability. In J. C. DeFries, R. Plomin, & D. W. Fulker (Eds.), *Nature and nurture during middle childhood* (pp. 262–280). Cambridge, MA: Blackwell.

Dale, P. S., Price, T. S., Bishop, D. V. M., & Plomin, R. (2003). Outcomes of early language delay: I. Predicting persistent and transient delay at three and four years. *Journal of Speech, Language, and Hearing Research*, *46*, 544–560.

Dale, P. S., Simonoff, E., Bishop, D. V., Eley, T. C., Oliver, B., Price, T. S., et al. (1998). Genetic influence on language delay in two-year-old children. *Nature Neuroscience*, *1*(4), 324–328.

Dionne, G., Dale, P. S., Boivin, M., & Plomin, R. (2003). Genetic evidence for bidirectional effects of early lexical and grammatical development. *Child Development*, *74*(2), 394–412.

Duncan, G. J., & Brooks-Gunn, J. (1997). *Consequences of growing up poor*. New York: Russell Sage Foundation.

Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D., & Pethick, S. J. (1994). Variability in early communicative development. *Monographs of the Society for Research in Child Development*, *59*, 1–173.

Goldsmith, H. H. (1991). A zygosity questionnaire for young twins: A research note. *Behavior Genetics*, *21*(3), 257–269.

Huston, A. C., McLoyd, V. C., & Garcia Coll, C. (1994). Children and poverty: Issues in contemporary research. *Child Development*, *65*, 275–282.

Jensen, A. R. (1998). *The g factor*. Westport, CT: Praeger.

Koeppen-Shomerus, G., Spinath, F. M., & Plomin, R. (2003). Twins and non-twin siblings: Different estimates of shared environment in early childhood. *Twin Research*, *6*, 97–105.

Leventhal, T., & Brooks-Gunn, J. (2000). The neighborhoods they live in: The effects of neighborhood residence on child and adolescent outcomes. *Psychological Bulletin*, *26*(2), 309–337.

Martin, M. (1995). Features of home environments associated with children's school success. *Early Child Development and Care*, *111*, 49–68.

Matheny, A. P., Wachs, T. D., Ludwig, J. L., & Phillips, K. (1995). Bring order out of chaos: Psychometric characteristics of the confusion, hubbub, and order scale. *Journal of Applied Developmental Psychology*, *16*, 429–444.

McCartney, K., Harris, M. J., & Bernieri, F. (1990). Growing up and growing apart: A developmental meta-analysis of twin studies. *Psychological Bulletin*, *107*, 226–237.

McGue, M., Bouchard, T. J., Jr., Iacono, W.G., & Lykken, D.T. (1993). Behavioral genetics of cognitive ability: A perspective. In R. Plomin, & G.E. McClearn (Eds.), *Nature, nurture, and psychology* (pp. 59–76). Washington, DC: American Psychological Association.

Neale, M. C, Boker, S. M., Xie, G., & Maes, H. H. (1999). *Mx: Statistical Modeling*. Box 126 MCV, Richmond, VA 23298: Department of Psychiatry. 5th Edition.

Neale, M. C., & Martin, N. G. (1989). The effects of age, sex and genotype on self-report drunkenness following a challenge dose of alcohol. *Behavior Genetics*, *19*, 63–78.

Oliver, B., Dale, P. S., Saudino, K., Petrill, S. A., Pike, A., & Plomin, R. (2002). The validity of a parent-based assessment of the cognitive abilities of three-year olds. *Early Child Development and Care*, *172*(4), 337–348.

Petrill, S.A. (2002). The case for general intelligence: A behavioral genetic perspective. In R. Sternberg, & E. Grigorenko (Eds.), *The general factor of intelligence. Fact or fiction?* (pp. 281–298). New York: Lawrence Erlbaum.

Petrill, S. A., Saudino, K. S., Wilkerson, B., & Plomin, R. (2001). Genetic and environmental molarity and modularity of cognitive functioning in 2-year-old twins. *Intelligence*, *29*, 31–43.

Pike, A., Iervolino, A., Eley, T. C., Price, T. S., & Plomin, R. (2004). *Environmental risk and young children's cognitive and behavioral development. Manuscript submitted for publication.*

Plomin, R. (1986). *Development, genetics, and personality*. Hillsdale, NJ: Erlbaum.

Plomin, R. (1994). *Genetics and experience: The interplay between nature and nurture*. Thousand Oaks, CA, USA: Sage Publications.

Plomin, R., & DeFries, J. C. (1985). Origins of individual differences in infancy. *The Colorado adoption project*. Orlando, FL: Academic Press.

Plomin, R., DeFries, J. C., McClearn, G. E., & McGuffin, P. (2001). *Behavioral genetics*. (4th ed.)New York: Worth Publishers.

Plomin, R., Fulker, D. W., Corley, R., & DeFries, J. C. (1997). Nature, nurture, and cognitive development from 1 to 16 years: A parent–offspring adoption study. *Psychological Science*, *8*(6), 442–447.

Price, T. S., Eley, T. C., Dale, P. S., Stevenson, J., & Plomin, R. (2000). Genetic and environmental covariation between verbal and non-verbal cognitive development in infancy. *Child Development*, *71*, 948–959.

Price, T. S., Freeman, B., Craig, I., Petrill, S. A., Ebersole, L., & Plomin, R. (2000). Infant zygosity can be assigned by parental report questionnaire data. *Twin Research*, *3*(3), 129–133.

Price, T. S., Petrill, S. A., Dale, P. A., & Plomin, R. (2004). A longitudinal multivariate genetic analysis of verbal and nonverbal cognitive abilities in early childhood. Manuscript submitted for publication.

Raftery, A. (1995). Bayesian model selection in social research. *Sociological Methodology*, *25*, 111–163.

Rowe, D. C. (1994). The limits of family influence: Genes, experience, and behavior. New York: Guildford Press.

Rutter, M., & Silberg, J. (2002). Gene–environment interplay in relation to behavioural and emotional disturbance. *Annual Review of Psychology*, *53*, 463–490.

Saudino, K. J., Dale, P. S., Oliver, B., Petrill, S. A., Richardson, V., Rutter, M., et al. (1998). The validity of parent-based assessment of the cognitive abilities of two-year-olds. *British Journal of Developmental Psychology*, *16*, 349–363.

Scarr, S. (1992). Developmental theories for the 1990's: Development and individual differences. *Child Development*, *63*, 1–19.

Scarr, S., & McCartney, K. (1983). How people make their own environments: A theory of genotype–environment effects. *Child Development*, *54*, 424–435.

Thal, D. J., O'Hanlon, L., Clemmons, M., & Fralin, L. (1999). Validity of a parent report measure of vocabulary and syntax for preschool children with language impairment. *Journal of Speech, Language, and Hearing Research*, *42*, 482–496.

Trouton, A., Spinath, F. M., & Plomin, R. (2002). Twins Early Development Study (TEDS): A multivariate, longitudinal genetic investigation of language, cognition and behaviour problems in childhood. *Twin Research*, *5*, 444–448.

Wachs, T. D. (1993). The nature–nurture gap: What we have here is a failure to collaborate. In R. Plomin, & G. E. McClearn (Eds.), *Nature, nurture and psychology* (pp. 375–391). Washington, DC: American Psychological Association.

Wachs, T. D. (1996). Known and potential processes underlying developmental trajectories in childhood and adolescence. *Developmental Psychology*, *32*, 796–801.