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# Intellectual Interest Mediates Gene-by-SES Interaction on Adolescent Academic Achievement

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## Abstract

Recent studies have demonstrated that genetic influences on cognitive ability and academic achievement are larger for children raised in higher socioeconomic status (SES) homes. However, little work has been done to document the psychosocial processes that underlie this gene-by-environment interaction. One process may involve the conversion of intellectual interest into academic achievement. Analyses of data from 777 pairs of 17-year-old twins indicated that gene-by-SES effects on achievement scores can be accounted for by stronger influences of genes for intellectual interest on achievement at higher levels of SES. These findings are consistent with the hypothesis that higher SES affords greater opportunity for children to seek out and benefit from learning experiences that are congruent with their genetically influenced intellectual interests.

### Keywords

Gene-by-Environment Interaction (G×E); Gene-environment Correlation (rGE); Academic Achievement; Intelligence; Socioeconomic Status (SES

Genetic influences are often found to account for upwards of 50% of individual differences in both general cognitive ability and academic achievement at the population level. Although some authors have argued that this large figure renders environmental explanations for socioeconomic disparities in cognition implausible (Herrnstein & Murray, 1994; Jensen, 1969, 1973), other developmental theorists have posited that genetic variance in cognitive ability and academic achievement may emerge, in part, *via* children's transactions with particular environmental experiences (Bronfenbrenner & Ceci, 1994; Dickens & Flynn, 2001). These transactional models of cognitive development represent an attempt to move beyond a focus on the relative magnitude of genetic versus environmental influences, and to move toward a more integrated understanding of how genes and environment combine and interact to produce complex behavioral phenotypes (Anastasi, 1958). In the current paper, we review the propositions of transactional models of cognitive development and discuss how transactional models can provide a framework for understanding recent findings that genetic variance in cognitive outcomes is moderated by socioeconomic status (SES). Next, we suggest that non-cognitive factors -- such as motivation, self-concept, and interests -- are “driving forces” in children's transactions with their environments, and that a de-coupling of children's intellectual interest and academic achievement may account for the decreased genetic variance in academic achievement for children living in lower SES homes. Finally, we present evidence from new analyses of the National Merit Twin Study supporting our hypothesis about the role of intellectual interest in gene-by-SES interaction on academic achievement.

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## Transactional Models of Cognitive Development

Plomin, DeFries, and Loehlin (1977) first described the processes by which genotypes could come to be differentially associated with environmental exposure, i.e., gene-environment correlation (rGE). Passive gene-environment correlations arise when children are raised by their biological parents, such that their rearing environments are influenced by some of the same genes that they inherit. Evocative gene-environment correlations arise when children's genetically influenced traits, features, and characteristics elicit particular environments from others. Finally, active gene-environment correlations arise when children seek out and choose experiences and environments that are consistent with their genetically influenced traits.

The typology of passive, evocative, and active rGE was applied to developmental theory by Scarr and McCartney (1983), who argued that children become increasingly autonomous over the course of development, such that passive gene-environment correlations weaken and active gene-environment correlations strengthen. A plausible, albeit perhaps counterintuitive, net effect of this process is that genes and environments become increasingly correlated with one another over the course of development. Thus genetically similar people (like MZ twins) will select increasingly similar environmental niches over time, and it is this convergence of environmental experience that maintains – or even increases – their phenotypic similarities. That is, Scarr & McCartney (1983, p. 427) suggested that genetic influences on complex psychological phenotypes are reinforced through on the on-going selection of environmental experiences that are "correlated with motivational, personality, and intellectual aspects of our genotypes." Elaborating on this perspective, Scarr (1992, p. 9) later hypothesized that the process of individuals sorting themselves into learning environments "depends on people having a varied environment from which to choose and construct experiences," a requisite that she argued is particularly likely to be absent for "children reared in very disadvantaged circumstances."

The process by which environmental experiences produce phenotypic differences was further elaborated on by Bronfenbrenner and Ceci (1994). Their *bioecological model* contends that environmental experiences are inextricably linked to genetic differences between individuals, and that the dynamic by which children and their environments mutually act upon one another is central to the realization of genetic potential for healthy development. Specifically, Bronfenbrenner and Ceci (1994) state that "human development takes place through processes of progressively more complex reciprocal interactions between an active [child] and the person, objects and symbols in [the child's] immediate environment." These reciprocal interactions are termed "proximal processes." A critical aspect of the bioecological model is its prediction that proximal processes will differ in their availability and quality across macro-environmental contexts, even in the range of "good enough" environments. This is a significant point of departure from Scarr (1993; also see Scarr & McCartney, 1983; Scarr 1992, and Scarr, 1996), who argued that environments other than severe deprivation were "functionally equivalent" (p. 1337).

Finally, Dickens and Flynn (2001) applied a transactional model of development specifically to the domain of cognitive abilities. They state the premise of transactional models simply: "higher IQ leads one into better environments causing still higher IQ, and so on." A major contribution of the Dickens and Flynn (2001) model is its conceptualization of how environmental experience aggregates over time. They suggest that environmental influences need not be large, but simply need to be consistent and recurring over long periods of development in order to have large effects on cognition and achievement. Moreover, environmental influences that are selected based on genetically influenced traits and preferences, rather than serendipitously encountered or externally imposed, are most likely

to be consistent over time (Caspi, Roberts, & Shiner, 2005; McAdams & Olson, 2010), and thus are precisely those environmental experiences that are most influential.

Considered together, transactional models of cognitive development posit that (a) individuals select (and are selected into) environments that are increasingly congruent with their own genetically influenced traits; (b) environments that are congruent with one's genotype are most likely to be consistent and recurring over the course of development; (c) recurring interactions with high-quality environments are necessary for the realization of genetic potential for healthy cognitive outcomes; and (d) macro-environmental contexts affect the availability and quality of environmental experiences important for cognition.

## Gene-by-SES Interactions in Cognitive Ability and Academic Achievement

One important macro-environmental context that may affect an individual's ability to select and interact with high-quality environmental experiences necessary for cognitive development and learning is socioeconomic status (SES). SES can be conceptualized as representing a family's level of “financial capital (material resources), human capital (nonmaterial resources such as education), and social capital (resources achieved through social connections)” (Bradley & Corwyn, 2002, p. 372). The differences in resources available to high versus low SES families are evident across multiple domains, including parental responsiveness, parental teaching, and level of cognitive stimulation (Bradley, Corwyn, McAdoo, & Coll, 2001). Children in higher SES homes are more likely to have developmentally appropriate books, be read to by a family member, be taught academic concepts, receive special lessons to improve specific skills, and be taken to the museum or theater. SES differences in environmental quality extend outside of the home, too (Kazdin, Kraemer, Kessler, Kupfer, & Offord, 1997). Compared to children growing up in higher SES homes, children growing up in lower SES homes are more likely to attend schools with inadequate instructional materials, fewer AP classes, fewer books and computers, non-functional science labs, and fewer academically-oriented or high-achieving classmates (Phillips & Chin, 2004). Moreover, lower SES children are perceived more negatively and receive less attention from teachers (McLoyd, 1998).

Given the relation between SES and children's opportunities to select and participate in the environmental experiences necessary for maximizing ability and achievement, transactional models of cognitive development predict that genetic variance in cognitive outcomes will be lower for children in low SES homes. Consistent with this prediction, there is an emerging body of research indicating that genetic influences on cognitive outcomes do indeed vary with SES. In a seminal paper, Rowe, Jacobsen, and van den Oord (1999) demonstrated that the heritability of verbal ability in a national sample of adolescents ranged from 72% in the most educated families to 26% in the least educated families. A subsequent reanalysis of this data by Guo and Stearns (2002), who incorporated multiple indices of parental SES, found that the moderating effect of SES could be best accounted for by parental ethnicity and unemployment. Next, using advances in quantitative techniques for modeling gene-environment interaction, Turkheimer, Haley, Waldron, D'Onofrio, & Gottesman (2003) reported that among low socioeconomic status 7-year olds, heritability of IQ was 10%, whereas among high socioeconomic status 7-year olds, heritability of IQ was 72% (see also Tucker-Drob, Turkheimer, & Harden, 2009). Harden, Turkheimer, & Loehlin (2007) reported a similar effect of parental income and parental education on the heritability of academic achievement in a sample of 17-year olds, and subsequent analyses indicated that their result was robust to assumptions about assortative mating and passive rGE between adolescent genotype and family income (Loehlin, Harden, & Turkheimer, 2009). Using a sample of middle-aged males, Kremen et al. (2005) found that heritability for word recognition (a component of reading ability) increased with higher parental education, accounting for 21% of the variance at the lowest parental education and 69% at the highest.

This effect, however, was driven by decreases in shared environmental variances with increasing education, rather than by increases in genetic variance. Very recently, Tucker-Drob, Rhemtulla, Harden, Turkheimer, and Fask (2011) demonstrated that gene-by-SES effects on cognitive ability emerge as early as 2 years of age. They reported that, in a nationally representative sample of 2 year old twins born in the United States in 2001, genetic influences on Bayley mental ability test scores approached zero for low SES children and approached 50% for high SES children. Finally, evidence consistent with a gene-by-SES effect on cognitive outcomes has also been found using a molecular genetic paradigm: Enoch, Waheed, Harris, Albaugh, and Goldman (2009) found a significant interaction between Val158Met, a functional polymorphism of the COMT gene, and educational attainment on cognitive abilities among adults. They found that, among Met allele carriers, educational attainment had a strong positive relation with test scores, whereas among Val/Val individuals, the positive relation between educational attainment and tests scores was much less pronounced. Overall, extant research suggests that there are gene-by-SES interactions for cognitive outcomes in childhood, adolescence, and adulthood.

## Non-Cognitive Factors as a Driving Force in Cognitive Development

Research on gene-by-SES interactions is largely consistent with the propositions of transactional models – that children actively select and respond to environmental experiences in accordance with their own genetically-influenced traits, and that this process is restricted by socioeconomic disadvantage, resulting in lower heritability of cognitive outcomes in lower SES homes. However, the specific factors that govern how a child or adolescent differentially selects or responds to options within the environment remain largely unexplored. While the Dickens and Flynn (2001) model emphasizes children's preexisting levels of ability and competence, we propose that *non-cognitive* factors – including levels of scholastic motivation, drive for achievement, intellectual self-concept, and intellectual interest – are also critical for the process of selecting environmental niches.

Figure 1 is a schematic illustration that represents the proposed role of non-cognitive factors in the selection of environments that influence cognition and achievement. At the corners of the triangle are three core class of constructs: (a) interests, intentions, and personality; (b) proximal environments (peer groups, coursework, activities, interpersonal interactions); and (c) cognitive abilities and achievement. Along the sides of the triangle are mechanisms that illustrate the bidirectional nature of the relations between the three core constructs. For example, interest in intellectual and academic pursuits is probabilistically related to experiencing high quality proximal environments (for example, enrollment in challenging coursework), through processes by which children actively seek out these experiences (for example, an adolescent enrolling in advanced placement English in hopes of improving chances of college admission) and by which they evoke these experiences from others (for example, a teacher recommending more difficult math course to an engaged and interested student). In turn, high quality proximal environments can result in further intellectual interest as a result of socialization processes, while also directly boosting achievement through the instructional process. (This schematic is not intended to be fully comprehensive; there are, of course, many other mechanisms that may underlie the relations among the three core sets of constructs.)

Furthermore, we predict that the strength of the mechanisms relating non-cognitive factors, achievement, and proximal environments will differ systematically with socioeconomic status. In a high SES environment, where children and adolescents can take advantage of a wide array of environmental experiences, interest and motivation will become tightly coupled with achievement: Intellectually interested adolescents will invest more time and effort into achievement-relevant behaviors (e.g., additional time studying), and they will preferentially select achievement-enhancing proximal environments (e.g., high achieving

peer groups, challenging coursework). More specifically, *genetic differences* in interest and motivation will become tightly coupled with achievement. This is because intellectual interest will result in an advantage for achievement *only* when it is systematic and recurring over long periods of development (Dickens and Flynn, 2001), and genetically-influenced aspects of personality are generally more developmentally consistent than are aspects of personality influenced by the immediate environment (Caspi et al., 2005). Thus, children and adolescents in high SES homes will be able to "convert" genetic differences in interest and motivation into achievement, resulting in higher overall heritability for achievement. In contrast, intellectual interest and achievement will be de-coupled for children in lower SES homes, who have restricted access to achievement-enhancing proximal environments (e.g., fewer opportunities for advanced math classes) and who have fewer resources to devote to achievement-relevant behaviors. Without the opportunity to "act out" genetically-influenced interest and motivation in the environment, genetic differences in non-cognitive factors become irrelevant for academic achievement. The net effect of this process will be reduced influence of genes related to intellectual interest on achievement, and lower overall heritability of achievement, for children living in lower SES homes.

### Hypotheses

The current study aims to test the role of intellectual interest in gene-by-SES interactions on academic achievement, using a sample of 777 adolescent twin pairs from the National Merit Twin Study (Loehlin & Nichols, 1976; 2009). Specifically, we test whether SES moderates the relation between genetic variance in intellectual interest and academic achievement. Transactional models of cognitive development predict that, in higher SES homes, genetic variance in intellectual interest is strongly coupled with academic achievement, resulting in higher overall heritability for academic achievement. Alternatively, in lower SES homes, where intellectually interested adolescents have restricted opportunities to select and respond to enriching proximal environments, the association between genetic variance in intellectual interest and achievement is decreased, resulting in lower overall heritability of achievement.

## Method

Data for the current project come from the National Merit Twin Study (Lohelin & Nichols, 1976). Harden, Turkheimer, & Loehlin (2007) have previously reported that in these data, heritability of a general achievement factor was higher for twins growing up in higher income homes. Here we extend this work by examining the extent to which this gene-by-environment interaction can be accounted for by socioeconomic differences in the genetic basis of the interest-achievement relation.

### Participants

Participants were sampled from approximately 600,000 American high school students (average age = 17 years) who took the National Merit Scholarship Qualifying Test (NMSQT) in 1962. Of these, 1507 pairs of same-sex twins were identified, 850 pairs of which agreed to participate. Zygosity was determined by a questionnaire that assessed twin similarity in childhood and the frequency with which they were confused by others (Nichols & Bilbro, 1966). These determinations were cross-validated using a subsample of 124 twin pairs of known zygosity, and found to be over 90% accurate. The current analyses were restricted to the 777 pairs for whom family income was reported (475 monozygotic pairs, and 302 dizygotic pairs). It is important to note that this sample size is comparable to those of many other twin studies (Boomsma, Busjahn, & Peltonen, 2002), but much smaller than most epidemiological studies. While power to detect gene-environment interaction effects is always a potential concern, previous studies using this data set have already found

significant gene-environment interaction effects on academic achievement (Harden et al., 2007), which is a testament to the power of this sample size.

## Measures

**Academic achievement** was measured with the NMSQT, which is composed of five subscales: English Usage, Mathematics Usage, Social Science Reading, Natural Science Reading, and Word Usage. For the purposes of the current paper the NMSQT selection score, which is a unit-weighted composite of the five subscale scores, were used as an index of general academic achievement. The twin pair correlation for this score was $r = .88$ for monozygotic twins and at $r = .64$ for dizygotic twins (both $P < .01$).

**Intellectual interest** was measured with the Intellectual Efficiency scale of the California Psychological Inventory. According to the Megargee (1972) “the manifest content [of the intellectual efficiency] scale reflects an interest in and enjoyment in intellectual pursuits: `I like to read about history' – [True]; and self-confidence and assurance: `I seem to be as capable and smart as most others around me'– [True].” According to McAllister (1996), very high scorers on the intellectual efficiency scale are “conceptual and intellectually oriented, tending to think or talk about problems more than act on them,” whereas low scorers “prefer to deal with tangible and concrete issues rather than with concepts or abstractions.” Importantly, intellectual efficiency is a subscale that correlates moderately with objective indices of cognition and achievement, but is based entirely on subjective self-report personality items. In the current dataset, this scale correlated with academic achievement at .44 ($P < .01$; based on only 1 twin per pair). The twin pair correlation for this scale was $r = .52$ for monozygotic twins and at $r = .33$ for dizygotic twins (both $P < .01$).

**Socioeconomic status** (SES) was indexed by parental report of family pre-tax income in a written questionnaire, with seven response categories ranging from less than $5,000 per year to over $25,000 per year. This range approximately corresponds to a range of less than $31,250 to over $156,250 in 2004 dollars. In the current dataset, this index correlated with academic achievement at .23 ($P < .01$; based on only 1 twin per pair), and with intellectual interest at .11 ($P < .01$; based on only 1 twin per pair).

## Analytical Methods

Data were analyzed using a series of four structural equation models of increasing complexity. First, we fit univariate main effects models separately to achievement and intellectual interest, in order to determine the overall magnitude of genetic influences on these phenotypes. Second, we fit univariate G×E models separately to achievement and intellectual interest, in order to determine whether the heritabilities of these phenotypes were moderated by SES. Third, we fit a bivariate main effects model, in order to test the contribution of genes to the *association* between intellectual interest and achievement. Finally, we fit a bivariate G×E model, in order to determine whether the relation between genetic variance in intellectual interest and achievement was moderated by SES, as would be predicted by transactional models of cognitive development. These models are described in more detail below. For all analyses, all variables were standardized relative to the means and standard deviations observed for the first twin in each pair. Analyses were carried out using the M*plus* computer program (Muthén & Muthén, 1998–2009) with maximum likelihood estimation.

**Step #1: Univariate main effects model—**A conventional biometric model for twins reared together specifies that a given phenotype is influenced by three statistically additive and independent unobserved components: additive genes (*A*), the shared environment, i.e., environmental influences that make children raised in the same home similar to each other

(*C*), and the non-shared environment, i.e., environmental influences that make children raised in the same home different from each other, plus measurement error (see Neale & Cardon, 1992, for more details regarding the parameterization of twin models). This basic model can be expanded to include measured covariates. Figure 2 illustrates the univariate main effects model for intellectual interest, including SES as a measured family-level covariate. In this model, the variances of the *A*, *C*, and *E* components are fixed to 1, and the correlation between *A* components in the first and second member of each twin pair is fixed according to genetic theory ($r$ = 1.0 in MZ twins and 0.5 in DZ twins). The paths from the A, C, and E components are freely estimated, and the square of these paths indicate the proportion of variance in the phenotype attributable to genes, shared environment, and non-shared environment. Thus the square of the *a* path gives the familiar heritability statistic ($h^2$) – the proportion of variance in the phenotype due to additive genes. It is important to note that because SES was measured at the family level, it was by definition an aspect of the shared environment. That is, controlling for SES reduces our estimate of the variance accounted for by the shared environment. Because SES is controlled for in all of our models, C should therefore be interpreted as family-level influences that are incremental to family-level SES. Univariate main effects models were fit separately for intellectual interest and academic achievement, in order to test the overall magnitude of additive genetic, shared environmental, and non-shared environmental influences on these phenotypes.

**Step #2: Univariate interaction model—**As described by Purcell (2002), the conventional univariate twin model can be easily expanded to test for gene-by-environment interaction. The univariate G×E model for intellectual interest is shown in Figure 3. This model is identical to the model illustrated in Figure 2, except that the paths representing the influence of additive genetic, shared environmental, and non-shared environmental influences are allowed to vary with SES. For example, the path from the additive genetic components to intellectual interest is modeled as ($a + a' \times$ SES), where a significant value for $a'$ would indicate that the amount of variance in intellectual interest due to genes changes with changing levels of SES.

**Step #3: Bivariate main effects model—**The univariate main effects models fit in Step #1 test the magnitude of genetic influence on each phenotype separately, but do not indicate how much genes contribute to the association between intellectual interest and achievement. That is, to the extent that higher intellectual interest is correlated with higher achievement, is this association due to common genetic influences? In order to test this, we fit a bivariate main effects model, shown in Figure 4. There are multiple ways to parameterize bivariate twin data; the current project uses a Cholesky model, which specifies an *a priori* ordering of the variables. Specifically, this model estimates the influence of genes, shared environment, and non-shared environment for intellectual interest; achievement is specified as a dependent variable that is regressed on the *A*, *C*, and *E* components of intellectual interest; and then residual variance in achievement that is independent of intellectual interest is also decomposed into *A*, *C*, and *E* components. Thus, in Figure 4, the $a_i$, $c_i$, and $e_i$ parameters represent the contributions of genes, shared environment, and nonshared environment to interest. The $a_b$, $c_b$, and $e_b$ parameters represent the extent to which genetic, shared environmental, and nonshared environmental influences on intellectual interest also predict academic achievement. Finally, the $a_a$, $c_a$, and $e_a$ parameters represent the contributions of genes, shared environment, and nonshared environment to the variance in achievement that is independent of interest.

**Step #4: Bivariate interaction model—**Just like the univariate models, the bivariate main effects model can be expanded to allow the genetic, shared environmental, and non-shared environmental influences to be moderated by SES. This bivariate interaction model is

shown in Figure 5. It is important to note that this model for tests for three different types of gene-by-SES interaction: (1) whether SES moderates genetic influence on intellectual interest ($a_i + a_i' \times$ SES); (2) whether SES moderates the association between genetic variance in intellectual interest and academic achievement ($a_b + a_b' \times$ SES); and (3) whether SES moderates genetic influence on academic achievement that is independent of intellectual interest ($a_a + a_a' \times$ SES).

The bivariate interaction model allows us to distinguish between at least two different theoretical scenarios. If the influence of genetic variance in intellectual interest on achievement is positively modified by SES, then gene-by-SES interaction for achievement would be due to greater genetic coupling between interest and achievement in high SES homes. Such a scenario would be consistent with our hypothesis that higher SES environments allow for greater opportunities to select and interact with experiences congruent with one's own genetically-influenced traits, leading to greater genetic coupling of intellectual interest and academic achievement. However, if only the genetic component of achievement that is independent of interest is modified by SES, then gene-by-SES interaction on achievement is independent of interest.

## Results

### Step #1: Univariate Main Effects Models

Parameter estimates from the univariate main effects models for academic achievement and intellectual interest are presented in the first and third columns of Table 1. It can be seen that there were statistically significant genetic, shared environmental, and non-shared environmental influences on both outcomes. For academic achievement additive genetic influences were estimated to account for 45% of the variance, shared environmental influences for 36%, and non-shared environmental influences (plus measurement error) for 13% (note that SES accounted for the remaining 6%). There were substantially greater within-twin pair differences for intellectual interest than for achievement. For intellectual interest additive genetic influences were estimated to account for 27% of the variance, shared environmental influences accounted for 21%, and non-shared environmental influences accounted for 49% (SES accounted for the remaining 2%).

### Step #2: Univariate Interaction Models

The parameter estimates for the univariate interaction models for achievement and intellectual interest are shown in the second and fourth columns of Table 1. As previously reported by Harden et al. (2007), the univariate interaction model for academic achievement fit the data significantly better than the univariate main effects (see Table 2 for a summary of model comparisons). Inspection of parameter estimates from the univariate interaction model indicates that the only interaction parameter that is significant is $a'$ – the moderating effect of SES on additive genetic influence. This parameter was estimated to equal 0.12 ($SE$ = 0.05), indicating that genetic influences on academic achievement are higher at higher levels SES. Figure 6 plots the variance in academic achievement attributable to additive genetic, shared environmental, and non-shared environmental influences as functions of SES, as implied by parameter estimates. It can be seen that the variance in achievement attributable to genes increases substantially from low to high SES levels. The same pattern can be observed in Table A1 of the Appendix, which reports MZ and DZ correlations for low, middle, and high SES families.

In contrast to the positive finding of a gene-by-SES interaction on academic achievement, there was no statistically significant evidence for such an interaction on intellectual interest: The univariate interaction model for interest did not fit significantly better than the

univariate main effects model, and none of the intereaction parameters (*a*', *c*', or *e*') were significantly different from zero. Based on these results, we cannot conclude that genetic influences are any more or less important for intellectual interest in advantaged environments versus disadvantaged environments.

### Step #3: Bivariate Main Effects Model

The bivariate main effects model extends the results from the univariate main effects model, by estimating the genetic, shared environmental, and non-shared environmental influences on each phenotype and on the association between interest and achievement. Parameter estimates for the bivariate main effects model are shown in the fifth column of Table 1. The $a_b$, $c_b$, and $e_b$ parameters were all significantly different from zero, indicating that both genetic and environmental factors contribute to the association between interest and achievement. Specifically, genetic influences on interest accounted for 8% of the variance in achievement, and shared environmental influences on interest accounted for 17% of the variance in achievement. Although significant, the effect of the non-shared environmental component of interest on achievement was very small, accounting for less than 1% of the variance in academic achievement after controlling for SES. These results demonstrate that it is genetic and shared environmental components of interest that account for the vast majority of the interest-achievement association. It is important to observe, however, that there was substantial genetic and environmental variation in achievement that is independent of interest, as indicated by the statistically significant $a_a$, $c_a$, and $e_a$ parameters. Specifically, genetic influences independent of interest accounted for 37% of the variance in achievement, shared environmental influences independent of interest accounted for 18% of the variance in achievement, and non-shared environmental influences independent of interest accounted for 12% of the variance in achievement.

### Step #4: Bivariate Interaction Models

The bivariate interaction model examines whether the extent to which academic achievement is influenced by the genetic, shared environmental, and non-shared environmental components of intellectual interest is moderated by SES. Moreover, it tests whether the genetic variance in academic achievement that is independent of intellectual interest is moderated by SES. That is, are genetic differences in intellectual interest more strongly coupled with academic achievement in high SES environments, and after accounting for this effect, is there any residual gene-by-SES interaction on academic achievement?

Parameter estimates from the full bivariate interaction model are shown in the sixth column of Table 1. Notably, the $a_b$' parameter was positive and significantly different than zero, indicating that genetic variance in intellectual interest contributed to academic achievement significantly more for children in higher SES homes versus lower SES homes. That is, adolescents' genetic predisposition to seek out and enjoy intellectually stimulating activities contributes to their academic achievement, but only when they are raised in high SES homes. This is consistent with our transactional model of cognitive development, which proposes that adolescents can “convert” their genetically-influenced interest and motivation into higher achievement only when in a macro-environmental context that allows them to select and interact with appropriate environmental experiences. Moreover, the $a_a$' parameter was not significantly different from zero, indicating that genetic influences on achievement that were independent of interest were not moderated by SES. This result indicates that gene-by-SES interactions on academic achievement can be accounted for by stronger influences of the genes for intellectual interest on academic achievement in higher SES homes. Note that in this model, there was also evidence for less nonshared environmental

variance in intellectual interest in high SES homes (i.e. the $e_i$' parameter was significantly less than 0).

The fit of the bivariate interaction model was only marginally significantly better than the fit of the main effects model. This is likely because the majority of the interactions modeled were not significantly different from zero. We therefore fit a model in which all nonsignificant interaction parameters were fixed to zero. In this model, the $a_b$' remained significantly different from zero, but the $e_i$' parameter was not significantly different from zero. Thus, as a final modeling step, we fixed all interaction parameters to zero, except for $a_b$' (the parameter representing the interaction between SES and the effect of genetic variance in intellectual interest on academic achievement). As shown in Table 2, this final model did not fit significantly worse than the full bivariate interaction model, and it fit significantly better than the bivariate main effects model that did not allow for any gene-by-SES interaction. The final model was therefore accepted as the best representation of the data.

Parameter estimates from final model are presented in the seventh column of Table 1. Because there is no $a_a$' interaction parameter, this model indicates that the gene-by-SES interaction on academic achievement (shown above in Figure 6) can be attributed to stronger influences of the genes for intellectual interest on academic achievement in higher SES homes. Figure 7 illustrates how SES moderates the etiology of academic achievement, based on the parameters from the final bivariate interaction model. The amounts of variance in intellectual interest due to genetic, shared environmental, and non-shared environmental factors do not vary with SES (left panel of Figure 7), and the same is true of variance in academic achievement that is independent of intellectual interest (right pane on Figure 7). However, the genetic component of intellectual interest is more predictive of achievement at higher levels of SES. The genetic component of intellectual interest accounts for almost zero variance in achievement at lower SES (−2 SD), but it accounts for approximately 30% of the variance in achievement at higher SES (+2 SD).

## Discussion

Behavioral genetic analyses of data from 777 pairs of high school twins indicated a link between academic achievement and genes for intellectual interest. At the population level, the magnitude of this link was modest; genes for intellectual interest accounted for only 8% of the variation in academic achievement. However, this proportion differed according to family socioeconomic status. At very low levels of SES, the genetic component of intellectual interest predicted close to 0% of the variation in academic achievement, whereas at high levels of SES, this proportion was approximately 30%. In contrast, the shared environment component of intellectual interested accounted for 17% of the variation in academic achievement, and the nonshared environment component of intellectual interest accounted for less than 1% of the variation in academic achievement, regardless of level of SES. The net effect was a gene-by-SES interaction in the direction of greater heritability of academic achievement in adolescents living in higher SES contexts.

These results are consistent with the theoretical proposition that socioeconomic disparities in children's opportunities to match their intellectual interest with congruent intellectually stimulating proximal environments is a major mechanism underlying the gene-by-SES interaction on adolescent cognition and achievement that has been observed in recent behavioral genetic research. Given the breadth of literature documenting the impact of SES on the day-to-day experiences of children and adolescents (Bradley & Corwin, 2002), we contend that adolescents raised in lower SES contexts 1) are afforded less opportunity to seek out intellectually stimulating scholastic experiences, peer groups, and interpersonal

interactions that match their levels of intellectual interest, and 2) receive fewer benefits to their intellectual growth and learning from work and effort put into intellectual and academic pursuits. Together, these mechanisms serve to make cognitive ability and academic achievement less related to intellectual interest in lower SES compared to higher SES groups. Specifically, borrowing from Dickens and Flynn (2001), we predicted that socioeconomic differences would be most evident in the *genetic* basis of the relation between intellectual interest and academic achievement, because components of personality traits that result from genetic predispositions are far more stable over development than are components that result from environmental experiences. That is, the nonshared environment is likely to represent short-lived, "one time" effects that are inconsistent across development, and are therefore likely not to exist with the intensity or duration necessary to have profound effects on cognitive development and learning (Dickens and Flynn, 2001; Turkheimer & Waldron, 2000). Genetic influences, on the other hand, are often developmentally consistent and long lasting, such that they result in cumulative and consistent exposure to environments that have effects on achievement.

## Limitations and Remaining Questions

**Relation between academic achievement and cognitive ability—**Readers are likely to wonder about the extent to which the current findings, which are based on objective measure of academic achievement, relate to gene-by-environment interaction research that has been conducted with conventional IQ scores (e.g. Turkheimer et al., 2003). There is a substantial body of research indicating that a general dimension of academic achievement is highly related to, although not synonymous with, a global dimension of cognitive ability, often termed general intelligence, or *g*. A study by Deary, Strand, Smith, and Fernandes (2007), for example, places the magnitude of this correlation at .81. There is also evidence (Thompson, Detterman, & Plomin, 1991) that while academic achievement may be more influenced by the shared environment than is cognitive ability, the two factors are largely influenced by the same genes. Finally, Tucker-Drob (2010) has recently demonstrated that while SES-related differences in the rates of development in multiple cognitive abilities and multiple domains of academic achievement outcomes can be substantially accounted for by way of a general developmental pathway, supplemental domain-specific pathways are necessary to account for SES-related differences in the development of some aspects of academic achievement. In sum, while the current results are likely to strongly relate to extant G×E findings with respect to general intelligence, it is possible that they also represent some achievement-specific developmental processes.

**The National Merit sample—**One limitation of sample used for these analyses is that, because the National Merit Qualifying Test was administered as part of a competition for college scholarships, the National Merit Twin sample lacked representation of very low socioeconomic status adolescents who did not plan to go to college. To illustrate, the average class ranking of students taking the NMQST was the 21$^{st}$ percentile. Moreover, the NMSQT sample consisted of very few minorities. The current findings are therefore most representative of the comparison between middle-class White families with upper-class White families. This selectivity strongly limits us from being able to generalize our findings to very poor families with very low achieving students, or to racial and ethnic minorities.

A related limitation concerns the fact that the National Merit Twin study was initiated in 1962, and may therefore be difficult to generalize to current adolescents, who have been raised in the present conditions of social-stratification. Since the 1970s, families with very low SES have become increasingly concentrated in geographically isolated communities, especially in urban areas (Massey, 1996; Wilson, 1987). To the extent that opportunity for scholastic achievement depends on the material resources that *communities* can provide their

children, rather than the resources of individual families (Brooks-Gunn, Duncan, Klebanov, & Sealand, 1993), then historical changes in the concentration of poverty might be expected to exacerbate the impact of SES on expression of genes related to achievement. This is speculative, however, and replication in contemporary samples is certainly warranted.

**Why no G×E on intellect interest?—**Another outstanding issue concerns why gene-by-SES effects were not observed for intellectual interest. We might have expected that if dynamic interest-achievement matching processes were the basis for the gene-by-SES effect on academic achievement, a similar gene-by-SES effect would be present for intellectual interest. That is, according to our proposed framework, interest and achievement mutually influence one another, such that interest (both directly and indirectly) affects achievement, and achievement (both directly and indirectly) affects interest. It is of note that, although not statistically significant, the *a*', *c*', and *e*' parameter estimates in Table 1 for the univariate interaction model of intellectual interest were in fact consistent with such an effect. It is possible that, if the sample had been larger or more diverse, we would have had the power to detect an interaction on interest at statistically significant levels. Another possibility is that while the academic achievement measure used was psychometrically very strong (it was, for example, a composite of scores from five highly correlated subscales), the intellectual interest measure used may have been somewhat weaker, rendering subtle G×E effects harder to detect. Finally, it is possible that the directional relation from interest to achievement is more affected by differences in socioeconomic opportunity than is the directional relation from achievement to interest. This could help to explain why a robust gene-by-socioeconomic status interaction held for the variance in achievement that was predicted by interest, but did not hold for any other variance components.

**Power—**It is also important to comment on the how the size of the current sample may have affected our results. We analyzed data from 777 pairs of twins, which is a sample size comparable to that of many other contemporary twin studies (Boomsma, Busjahn, & Peltonen, 2002), but much smaller than most epidemiological studies. It is possible that our analyses may have only been powered to detect large and robust gene-by-environment interactions, and may have missed more subtle interactions. A testament to the power of this study is the fact that we were able to detect a significant and robust interaction between SES and genes for interest that accounted for individual variation in achievement. After accounting for this interaction, the previously detected interaction between SES and genes for achievement was reduced to nonsignificant levels, suggesting that intellectual interest completely mediated the gene-by-SES effect on achievement. However, it is possible that if we had obtained an even larger sample of twins, this residual gene-by-SES effect would have remained statistically significant, thus indicating only partial mediation. Of course, logistical considerations inevitably force researchers to make difficult decisions regarding the tradeoff between obtaining large samples and obtaining high quality, detailed, and reliable, multivariate measurements. Typically, in order to overcome the substantial challenges to collecting large samples of individuals, researchers reduce the breadth, depth, and precision of measurement. Continued progress in identifying and testing the psychosocial mechanisms underlying gene-environment effects on academic achievement will require large genetically informed studies with broad arrays of high quality measures.

**Developmental specificity of mechanisms for G×E—**The current results are consistent with the existence of socioeconomic disparities in the success of a gene-environment transaction in which adolescents select proximal environments that are consistent with their levels of intellectual interest. It is likely, however, that earlier in life, socioeconomic status is likely to have its most profound effect on the success of evocative processes, by which child temperaments elicit specific types of stimulation from caregivers

(Bradley & Corwin, 2002; McLoyd, 1998). Therefore, while the current study suggests that gene by SES interactions in adolescents' academic achievement are largely attributable to SES differences in an active “niche-picking” process, it is possible that gene-by-SES interactions on mental abilities in very early childhood are results of socioeconomic differences in evocative processes (Tucker-Drob, et al., 2011).

## Future Directions

**Specific interests and specific cognition and achievement outcomes—**The current project exemplifies the benefit of integrating research on cognition and achievement with research on personality. The personality-achievement intersection is historically understudied (Chamorro-Premusic &Furnham, 2005), yet is likely to be integral to understanding why children differ in their abilities to achieve their cognitive and academic potentials. Future research will benefit from examining the specific loci of these effects by measuring a wide variety of personality, ability, and achievement constructs, and examining how they mediate the heritable variation in one another. Although a general factor can account for large proportions of individual differences in many different cognitive ability and academic achievement domains, researchers are increasingly recognizing that there are substantial individual differences in specific cognitive domains that are unaccounted for by a general factor, and which are potentially governed by domain-specific developmental processes (Tucker-Drob, 2009). There is similarly a growing appreciation for the unique properties of facets of larger personality traits (DeYoung, Quilty, & Peterson, 2007), and how different facets may differentially relate to cognitive abilities (Moutafi, Furnham, & Crump, 2006).

**Specific aspects of socioeconomic status and specific proximal environments—**Just as it will be necessary to measure specific interests and specific cognition and achievement outcomes, it will be necessary for future research to make use of specific measures of both macro-environments and proximal environments. Socioeconomic status is likely to serve as a proxy for a number of macro-environmental contexts, such as population density, residential instability, and school quality, to name a few. Future research will certainly benefit from examining how such indices relate to the strength of dynamic processes by which children select their proximal environments. It will be equally important for future research to make use of specific measures of the proximal environments that children are likely to select. Such proximal environments might include peer groups, course work, extracurricular activities, and time spent reading and studying.

**Longitudinal changes across development—**An additional future direction will be to examine the hypotheses tested here using longitudinal data. The current project made use of a cross-sectional approach in order to make inferences about a dynamic process that unfolds over time. Longitudinal measures of children's interests, abilities, and both macro-contextual and proximal environments from infancy through adolescence will be required to capture more fully the processes by children evoke and select individual experiences that are congruent with their interests, intentions, motivations, and self concept. Obtaining such measures across a wide range of ages would be of particular value for examining when during childhood the intersection between intellectual interest and achievement emerges. Intellectual interest is likely to become important for academic achievement much earlier than adolescence, given evidence suggesting that even young children's learning experiences are influenced by their own behaviors (Lugo-Gil & Tamis-LeMonda, 2008; Rain, Reynolds, Venables, & Mednick, 2002). Furthermore, longitudinal data would be valuable for examining whether interest-achievement relations strengthen over development. There are at least two reasons to expect such a strengthening to occur, at the very least for children living in high SES contexts. First, as children get older they have greater opportunity to

autonomously select their curricular and extracurricular activities, as well as their peer groups (Scarr & McCartney, 1983). Second, early educational choices and learning experiences are likely to both bolster achievement and reinforce the interests and motivations that were the basis for those initial choices. Caspi, Roberts, and Shine (2005) articulated this perspective as their *corresponsive principle*: "the most likely effect of life experience on personality development is to deepen the characteristics that lead people to those experiences in the first place."

### Conclusion

In summary, behavioral genetic models were fit to data on intellectual interest and academic achievement from 777 pairs of monozygotic and dizygotic twins from the National Merit Twin Study. There was statistically significant evidence that the variance in academic achievement explained by genes varied positively with SES. In the context of a bivariate model, this effect could be accounted for by stronger influences of the genes for intellectual interest on academic achievement in higher SES homes. These results are consistent with the hypothesis that higher SES allows children to better convert their intellectual interest into academic achievement through a process of gene-environment correlation.

## Acknowledgments

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## Appendix

**Table A1**

Monozygotic (MZ) and Dizygotic (DZ) twin correlations for academic achievement in lower, middle, and higher income families.

| Group | Family Income (1–7 scale) | Family Income Range (1962 dollars) | $N_{MZ}$ | $N_{DZ}$ | $r_{MZ}$ | $r_{DZ}$ | $h^2$ | $c^2$ | $e^2$ |
|---|---|---|---|---|---|---|---|---|---|
| Lower SES | 1, 2 | Less than $5000/year to $7499/year | 188 | 104 | .840 | .657 | 36.6% | 47.4% | 16.0% |
| Middle SES | 3, 4 | $7,500/year to $14,999/year | 205 | 144 | .882 | .626 | 51.2% | 37.0% | 11.8% |
| Higher SES | 5, 6, 7 | $15,000/year to $25,000/year and over | 82 | 54 | .902 | .573 | 65.8% | 24.4% | 9.8% |
| Full Sample | 1,2,3,4,5,6,7 | Less than $5000/year to $25,000/year and over | 475 | 302 | .880 | .637 | 48.6% | 39.4% | 12.0% |

Note: $h^2 = 2(r_{MZ} - r_{DZ})$. $c^2 = r_{MZ} - 2(r_{MZ} - r_{DZ})$. $e^2 = 1 - r_{MZ}$. $h^2$, $c^2$, and $e^2$ estimates reported here for the full sample differ slightly from those reported in the body of the paper, because results reported in the body of the paper were produced by structural equation models that controlled for the main effects of SES.

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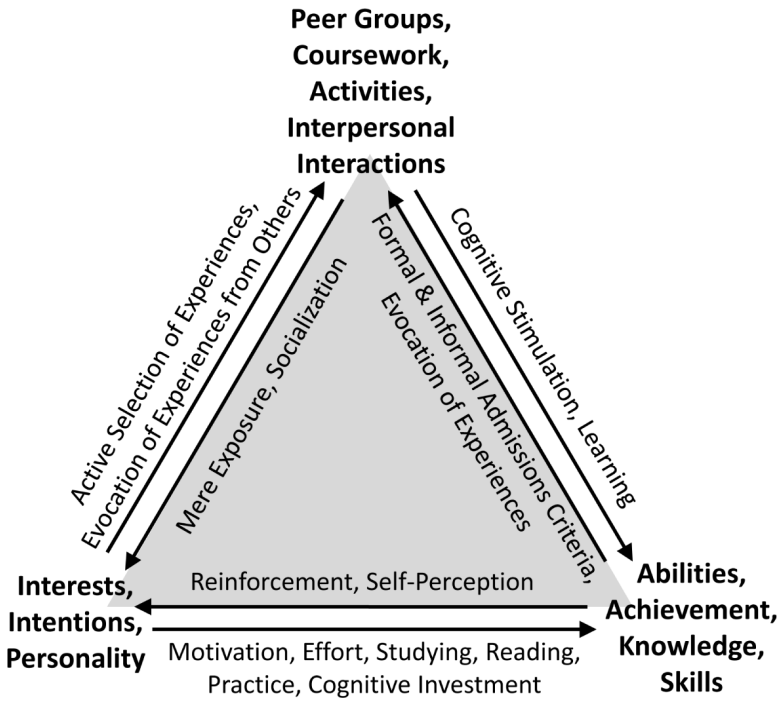


**Figure 1.**
A conceptual model for the mutual relations between Interests, Proximal Environments, and Achievement.

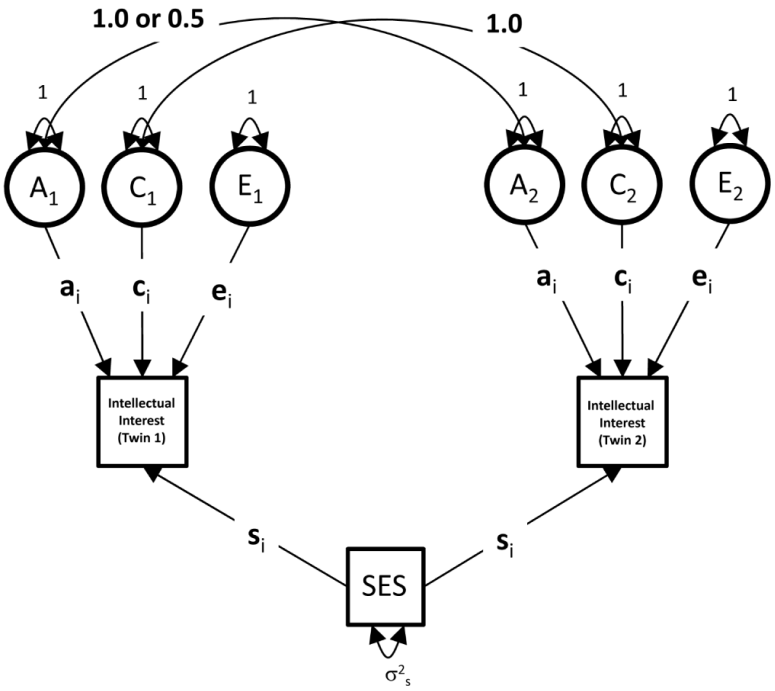


**Figure 2.**
A path diagram for the univariate main effects model of intellectual interest in twins.

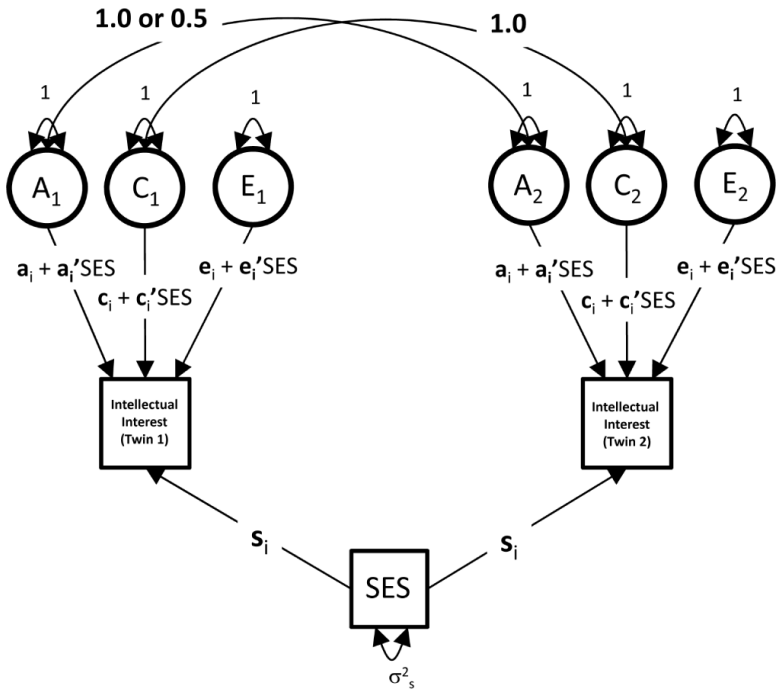


**Figure 3.**
A path diagram for the univariate interaction model of intellectual interests in twins.

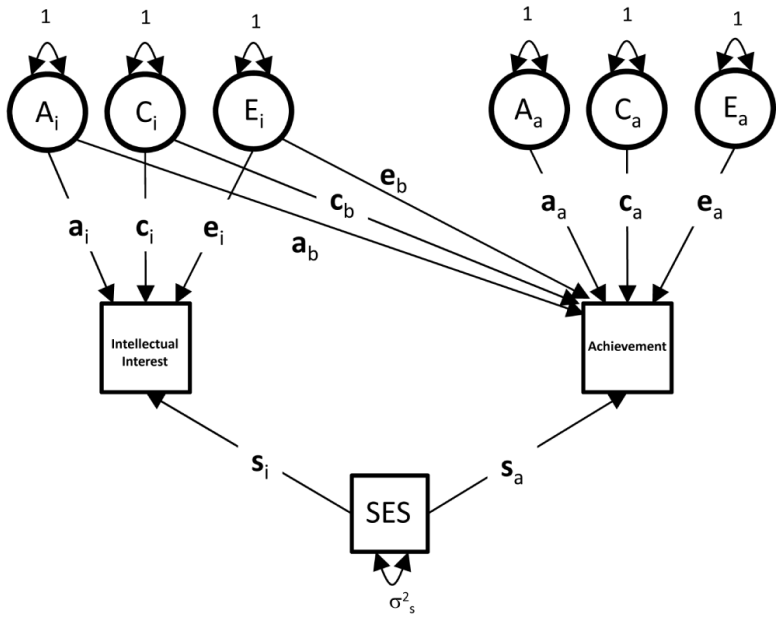


**Figure 4.**
A path diagram of the bivariate Choleksy model of intellectual interest and academic achievement. Note: Only one twin per pair is shown.

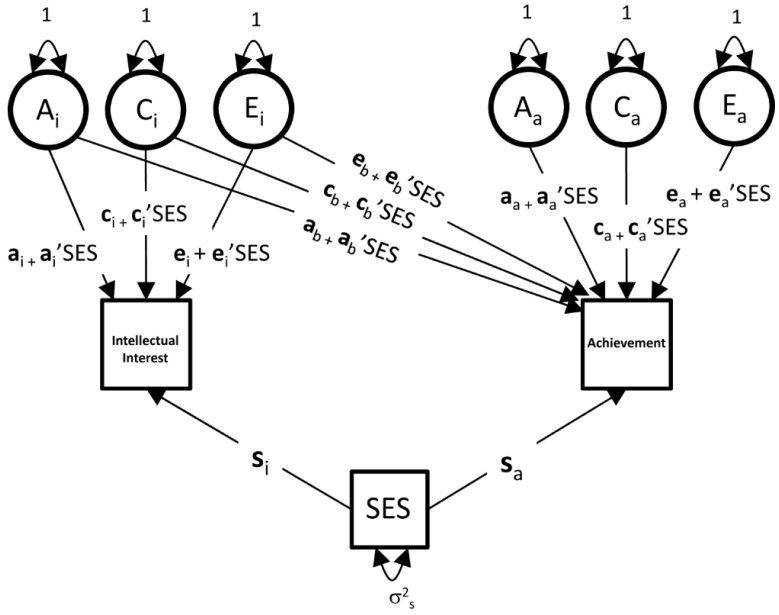


**Figure 5.**
A path diagram of the bivariate interaction model for intellectual interest and academic achievement. Note: Only one twin per pair is shown.

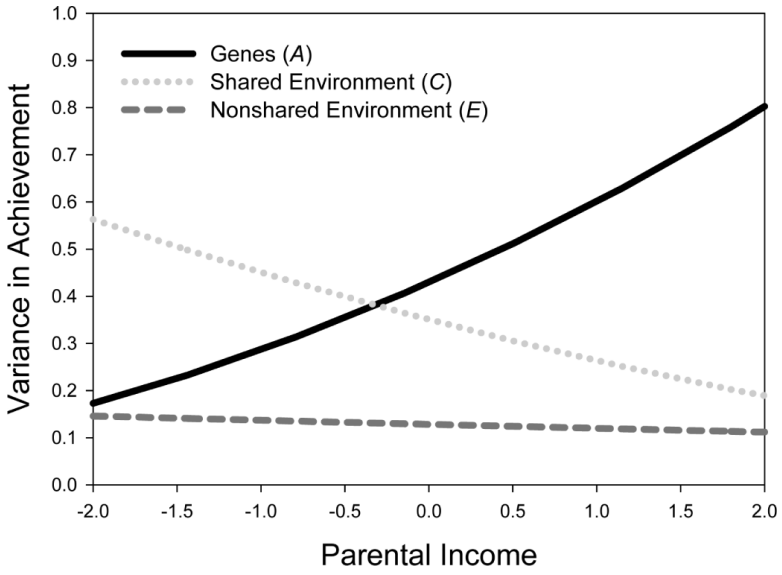


**Figure 6.**
Genetic and environmental contributions to academic achievement as functions of socioeconomic status.

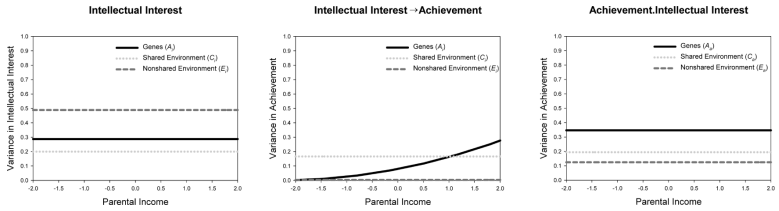


**Figure 7.**

Genetic and environmental components of intellectual interest, the regression of academic achievement on intellectual interest (Intellectual Interest → Achievement), and the variance in academic achievement that is unique of intellectual interest (Achievement. Intellectual Interest), as functions of socioeconomic status.

**Table 1**

Parameter Estimates From Univariate and Bivariate Twin Models.

| | Univariate Models | | | | | | | | Bivariate Models (Interest → Achievement) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Achievement | | | | Interest | | | | | | | | | |
| | 1. Main Effects | | 2. Interaction | | 3. Main Effects | | 4. Interaction | | 5. Main Effects | | 6. Interaction | | 7. Final Model | |
| **Parameter** | **Estimate** | **SE** | **Estimate** | **SE** | **Estimate** | **SE** | **Estimate** | **SE** | **Estimate** | **SE** | **Estimate** | **SE** | **Estimate** | **SE** |
| $a_i$ | | | | | **0.523** | **0.110** | **0.503** | **0.127** | **0.538** | **0.106** | **0.490** | **0.124** | **0.536** | **0.095** |
| $a_i'$ | | | | | | | 0.101 | 0.068 | | | 0.111 | 0.068 | | |
| $c_i$ | | | | | **0.459** | **0.113** | **0.460** | **0.123** | **0.445** | **0.117** | **0.470** | **0.109** | **0.447** | **0.104** |
| $c_i'$ | | | | | | | −0.100 | 0.083 | | | −0.103 | **0.07** | | |
| $e_i$ | | | | | **0.700** | **0.022** | **0.699** | **0.023** | **0.698** | **0.022** | **0.700** | **0.022** | **0.699** | **0.021** |
| $e_i'$ | | | | | | | −0.037 | 0.020 | | | − **0.04** | **0.02** | | |
| $a_b$ | | | | | | | | | **0.274** | **0.107** | **0.283** | **0.105** | **0.281** | **0.086** |
| $a_b'$ | | | | | | | | | | | **0.135** | **0.068** | **0.122** | **0.043** |
| $c_b$ | | | | | | | | | **0.412** | **0.138** | **0.381** | **0.108** | **0.408** | **0.106** |
| $c_b'$ | | | | | | | | | | | 0.014 | 0.08 | | |
| $e_b$ | | | | | | | | | **0.061** | **0.016** | **0.057** | **0.016** | **0.059** | **0.016** |
| $e_b'$ | | | | | | | | | | | −0.023 | 0.015 | | |
| $a_a$ | **0.668** | **0.044** | **0.655** | **0.045** | | | | | **0.609** | **0.056** | **0.586** | **0.055** | **0.589** | **0.055** |
| $a_a'$ | | | **0.120** | **0.046** | | | | | | | 0.055 | 0.045 | | |
| $c_a$ | **0.596** | **0.055** | **0.592** | **0.059** | | | | | **0.430** | **0.130** | **0.447** | **0.098** | **0.441** | **0.103** |
| $c_a'$ | | | −−0.079 | 0.064 | | | | | | | −0.103 | 0.079 | | |
| $e_a$ | **0.359** | **0.012** | **0.358** | **0.012** | | | | | **0.353** | **0.011** | **0.352** | **0.011** | **0.353** | **0.011** |
| $e_a'$ | | | −0.012 | 0.011 | | | | | | | −0.010 | 0.011 | | |
| $s_i$ | | | | | **.127** | **.030** | **.127** | **.031** | **.130** | **.030** | **.135** | **.031** | **.135** | **.030** |
| $s_a$ | **.243** | **.032** | **.251** | .034 | | | | | **.242** | **.032** | **.253** | **.034** | **.253** | **.034** |

*Note*. Parameters in **bold** are significant at $P < .05$.

## Table 2

Model Fit Comparisons.

| Comparison | Chi Square | *df* | *P* value |
|---|---|---|---|
| Main Effects Achievement vs. Interaction Achievement | 7.970 | 3 | **0.047** |
| Main Effects Interest vs. Interaction Interest | 2.962 | 3 | 0.398 |
| Main Effects Bivariate vs. Interaction Bivariate | 15.902 | 9 | 0.069 |
| Interaction Bivariate vs. Reduced Bivariate | 7.02 | 8 | 0.534 |
| Main Effects Bivariate vs. Reduced Bivariate | 8.882 | 1 | **0.003** |