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Socioeconomic Status and Genetic Influences on Cognitive Development

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Abstract

Accurate understanding of environmental moderation of genetic influences is vital to advancing the science of cognitive development as well as for designing interventions. One widely- reported idea is increasing genetic influence on cognition for children raised in higher socioeconomic status families, including recent proposals that the pattern is a particularly US phenomenon. We use matched birth and school records from Florida siblings and twins born in 1994-2002 to provide the largest, most population-diverse consideration of this hypothesis to date. We find no evidence of SES moderation of genetic influence on test scores, suggesting that articulating gene-environment interactions for cognition is more complex and elusive than previously supposed.

Keywords: genetic influences; environmental moderation; gene-environment interactions; registry data

Introduction

That genes and environments combine to influence cognitive development is broadly recognized, yet clear specifications of how they combine remain elusive. Behavioral geneticists have found that genetic differences are more influential on cognition for persons raised in more advantaged environments, a result sometimes called the Scarr-Rowe interaction (*1*). The animating idea is that social disadvantage compromises the extent to which a child's genetic potential is realized. As a result, the ultimate influence of genetic endowment is lower in these environments, which implies also that higher heritability estimates reflect improved social conditions (*2-4*).

While there have been striking findings supporting the hypothesis (*5-10*), results are inconsistent (*11-15*), and a recent meta-analysis indicates only modest support (*16*). Notably also, the meta- analysis finds that the hypothesis has fared much better in studies of US samples than samples elsewhere, mainly Northern/Western Europe and Australia.

Potential explanations of this divergence include the possibilities that socioeconomic variation in the US is simply larger in magnitude, or that the US educational system is less effective at helping disadvantaged students reach their potential (*16*). Child poverty rates, rates of children living in homes with deprived educational resources, and inequality in educational achievement are all higher in the US than in countries in which null results have been reported (*17-18*). If heritability of cognition reflects opportunity, then differential heritability by socio-economic status (SES) in the US could be interpreted as a consequence of some combination of social disparities in the US. Of course, any such conclusion is predicated upon establishing that results really are different for the US.

Current study

This study considers the hypothesis using unique population-level administrative data that match birth and public school records for all Florida children born between 1994 and 2002. Birth records were matched to school records on the basis of names, birthdates, and social security numbers. The rate of these matches is consistent with expectations from Census data about the percentage of children born in Florida that subsequently attend Florida public schools. Our investigations indicate that rates of being able to match records for one twin but not the other is extremely low and unlikely to bias findings (*19*). By using state records, we can assemble a sample with longitudinal test score data that is an order of magnitude larger than all previous studies (24,640 twins with matched birth-school records and test score information).

Our method does not depend on locating, recruiting, and retaining twins to participate in data collection efforts, which is important because this often considerably reduces the representation of twins from disadvantaged backgrounds in study samples. Having data from Florida allows us to represent a broader range of socioeconomic background better than past work, as the state has comparable or greater socioeconomic inequality than any other population for which the hypothesis has been considered so far. In our twin sample, 25.6% of mothers are African- American, 18.0% are Hispanic, 14.5% are age 21 or younger, and 32.0% are unmarried at time of birth. While an earlier survey-based study of Florida children found evidence of SES moderation of the heritability of achievement test scores, that sample had only 577 twin pairs and measured socioeconomic status of schools rather than families themselves *(20)*.

Twin studies in behavioral genetics typically identify the genetic contribution to an outcome's variance using the difference in genetic relatedness between monozygotic (MZ, "identical") and dizygotic (DZ, "fraternal") twins. Trait heritability is then a function of the intraclass correlations – the ratio of between-pair variance to total variance – between samples of

MZ and DZ twins drawn from the same population (*21*). A hypothesis that SES moderates heritability implies that the relationship between intraclass correlations differs over SES groups. Administrative data generally do not contain information on zygosity. But since all opposite-sex (OS) twin pairs are DZ while same-sex (SS) twin pairs contain approximately a 50-50 mix of MZ and DZ twin pairs, on average SS twin pairs will be genetically more similar than OS twin pairs. One remaining complication with using administrative data is that among DZ twins, SS twins could also be more similar to one another on an outcome than OS twins for non-genetic reasons, most obviously via any consequence of being the same sex. We address this challenge in two ways. First, we standardize test scores within sexes, so twin similarity will be measured independent from any mean or variance differences between sexes. Second, differences between SS and OS twins will be compared to differences between SS and OS siblings who are close in age but not twins.

The size and representativeness of administrative data are benefits to be weighed against the limitation of not having zygosity measures. That said, studying the Scarr-Rowe interaction with data in which zygosity is known involves other assumptions, which may be more problematic than is broadly appreciated. The variance components estimated in this work are population parameters, as are terms for the moderation of these components by SES. Yet the design and differential recruitment of many twin studies complicate the definition of the target population that the estimates produced by these studies are supposed to represent. For that matter, given the strong association between SES and test scores, estimated interactions have some dependence on the metrics by which SES and test scores are specified in models, but there has been little articulated reason beyond convention to favor any particular metric over others. None of this is intended to dismiss prior work. But, drawing inferences about biosocial interaction from models estimating statistical interactions is a thorny matter, involving substantial assumptions that are not simply dispelled by having data on twins' zygosity. Instead, evidence across multiple research designs is needed *(23-24)*.

Results

Figure 1 shows the relationship between one measure of SES – maternal education – and scores on the Florida Comprehensive Assessment Test for all pairs in the sample (Supporting Information contains parallel results for SES measure based on median income, PCA based SES indexes and for an alternative achievement test). Many studies show positive relationships between these various SES measures and cognitive functioning (*25-30*). Children whose mothers did not finish high school were about 0.5 standard deviations below the overall mean, compared to 0.5 standard deviations above the mean for children whose mothers have completed college.

Pair-level intraclass correlations (ICCs) in Figure 2 show that data are consistent with substantial genetic influence on test scores. For twins, a sizable difference exists between the ICCs for SS versus OS twins. The difference is several times larger than the corresponding difference between SS and OS non-twins, as we would expect if the primary cause of the twin difference is that about half the SS twins are MZ twins. Nevertheless, we can also see that SS non-twins are more similar than OS non-twins, and that OS twins are more similar than OS non-twins. This pattern implies that sex-similarity and twin status do have their own, albeit small, influence on pair similarity.

Data are thus consistent with familiar results that cognitive achievement differs over SES and that MZ twins have more similar cognitive achievement than DZ twins. To consider whether the data also provide evidence of a Scarr-Rowe interaction, we follow Turkheimer and Horn's review of the literature, which summarizes existing evidence as a combination of two phenomena (*21*). We consider each in turn using Figure 3, which presents within- and between- pair variances for SS and OS twins.

First, Turkheimer and Horn indicate that “the between-pair variance of MZ pairs decreases in poor environments” (*21*, p.63). Contrary to this relationship, we find that the between-pair variance of SS twins is actually lowest in the highest SES families. Given that SS twins are a relatively equal combination of MZ and DZ twins, one possibility is that a pattern supporting the hypothesis among MZ SS twins is masked by an even stronger pattern in the opposite direction among DZ SS twins. However, Figure 3 shows that corresponding results for OS twins (all of whom are DZ) give no indication of such a pattern. Between-pair variances in achievement test scores for high-school educated parents of OS twins are higher in all cases than it is for parents without a high school diploma.

Second, Turkheimer and Horn report that “the within-pair variance of MZ twin pairs increases at lower levels of SES: poverty appears to have the effect of making MZ twins more different from each other” (*21*, p.61). We would therefore expect in our data that the within-pair variance for same-sex twins in which the mother did not graduate from high school would be higher than the variance for same-sex twins in which the mother has a high school diploma. But in none of the SS twin comparisons in Figure 3 is this the case.

As before, one might be concerned that a contrary pattern among DZ twins is masking the effect, since some same-sex twins are DZ. However, this possibility is again contradicted by results shown in Figure 3 for opposite-sex twins, in which the pattern of results is opposite of what would be necessary for such masking to happen. We find very similar results for alternative measures of SES (Supporting Information, Figures S10, S18 and S22).

For older children and math tests, there may be an indication of higher within-pair variance for SS twins with high-school versus college educated mothers. This is the result closest to the expectations of the hypothesis. Even here, however, we observe that a similar pattern is present in these cases for opposite-sex twins, which strengthens the alternative possibility that the result among same-sex twins could be driven by DZ pairs, rather than by MZ pairs as entailed by a Scarr-Rowe interaction.

Turkheimer and Horn (*21*) show that the combined result of changing variance is an increasing divergence of intraclass correlations between MZ and DZ twins, as such divergence implies higher heritability estimates. Accordingly, we would expect the difference in ICCs between SS and OS twins to diverge as SES increases. We present ICCs by maternal education in Figure 4, and, contrary to expectations from Turkheimer and Horn, we observe the opposite pattern. Figure 4 also shows that differences are much smaller and inconsistently signed between SS and OSnon-twin siblings, which contradicts the possibility that our results diverge from the hypothesis due to SES moderation of sex difference per se. We find very similar results for alternative measures of SES (Supporting Information, Figures S11, S19 and S23).

A different method of estimating the interaction is to adapt a model presented by Purcell (31) and used in the meta-analysis by Tucker-Drob and Bates (16). This model extends the conventional ACE model that estimates additive genetic effects (A), shared environment (C), and non-shared environment (E). The extended model includes a separate term for variance accounted for by the socioeconomic status measure (M), along with terms for moderation by socioeconomic status (A’, C’, E’). In these models, A indicates the estimated narrow-sense heritability for someone with average SES. This method is more conventional but also involves stronger metric assumptions.

Table 1 presents these results. The prediction is that the moderator term for the additive genetic component (A’) would be positively signed and statistically significant. Our results over different outcomes uniformly contradict this prediction. We also test whether our results depend on assumptions about the proportion of MZ twins in the SS twin group, but, over the range of plausible assumed values we tested (0.4 to 0.6), the interaction terms were uniformly signed in the wrong direction from the prediction, but not always statistically significantly so (Supporting Information, Table S3). We have also explored two alternative more continuous measures of SES based on PCA analyses. Again, the interaction terms were uniformly signed in the wrong direction and not always significant (Supporting Information, Tables S4 to S7).

To address the possibility that results may be confounded in one way or another by SES differences by race, we also conducted analyses in which we restricted the sample to children with white mothers (whites are the largest race/ethnic group in the sample). We further conducted analyses restricting the sample to mothers up to age 30, for whom rates of IVF use are extremely low (*32*), in case SES differences in use of IVF treatments could distort results for DZ twins (DZ – but not MZ – twinning rates are much higher when IVF is used). In both cases, as well as other analyses also reported in the Supporting Information, our substantive conclusion remains the same: no evidence of a Scarr-Rowe interaction.

Discussion

While past research has found stronger evidence for a Scarr-Rowe interaction in the US than elsewhere, we fail to find evidence of increasing genetic influence on the cognitive similarity of twins as SES increases. Ours is the first analysis to make use of large-scale population-level administrative data in the US where population inferences are not compromised by patterns of successful recruitment into a survey, especially among low-SES families. Our results do suggest that the mixed results in this literature cannot be explained by lack of SES diversity in some samples or by differences between the US and other nations.

Trying to understand why we fail to find an interaction when (some) others have is difficult. For example, Kovas et al (*33*) report higher grade-school heritabilities for literacy and numeracy versus IQ test scores, raising the possibility that our results could differ if we had IQ test results instead of math and reading achievement tests. However, the differences reported in that paper are present for younger but not older children while our results are consistent across ages 8 to 14. Reviews of the literature have also cited other studies using achievement tests as evidence for the interaction (*21*).

Perhaps our lack of direct zygosity measurement is the culprit, but the study that launched this literature also compared same-sex and opposite-sex twins (*1*), and our study's sample size surmounts the concerns about statistical power raised regarding that study (*22*). Maybe the absence of private schools in our sample is an issue, as children of higher SES families are more likely to attend private schools. However, decades of research have failed to establish clear evidence of a broadly positive causal effect of private vs. public schools in the US, especially for children of more affluent families (*34*-*35*).

At a minimum, our findings indicate that the nature of the gene-environment interaction is less clear-cut than may have been supposed from smaller samples. How to effectively describe the interplay of genes and environments remains a profound scientific challenge, and we hope continued improvements in the availability of both administrative and genomic data will yield important progress in the years ahead. One potential frontier for future work would make use of molecular genetic data rather than studies of twin similarity. While early efforts to identify genetic correlates of cognitive ability faced substantial challenges (*36*), they have more recently become quite promising (*37*-*39*). As causal genetic variants for cognition become better established, one question will be whether they are more influential in some environments than others, and whether there will be a more systematic genomic pattern of greater cumulative influence in higher-SES environments. However, it may still be some time before sufficient sample sizes will be available to investigate this question fully.

Materials and methods

Data for the study are based on matched birth and school records obtained for all children who were born in Florida between 1994 and 2002 and subsequently educated in a Florida public school. Birth certificates were matched to Education Data Warehouse by Florida Department of Health and Florida Department of Education, using four variables: first and last name, date of birth, and social security number. To maximize correct matches, transposition of letters or numbers was allowed in up to two instances as long as the transposition did not match more than one record. Children were included if they (1) were born in Florida, (2) remained in Florida until school age, and (3) attended Florida public schools.

Twins were ascertained by plurality information on the birth certificate, as well as the same date of birth and maternal characteristics. Non-twin siblings were ascertained by residential address in schooling, and were linked back to the relevant students' birth records to check that students we believed to be siblings were actually siblings (e.g. by comparing maternal characteristics such as date of birth). For families with more than two non-twin siblings in eligible cohorts, we constructed our sample of non-twin-sibling pairs by taking the two closest in age.

Overall, 80.7% of all children born in Florida, and 79.5% of all twins born in Florida, were matched to school records. This aligns closely with the 80.9% rate of kindergarten-age children born in Florida and attending Florida public schools based on data from the American Community Survey.

Florida has a larger population (20.3M in 2015) than several nations in which the Scarr-Rowe interaction has been previously studied (e.g., Netherlands, Sweden). Relative to other US states, Florida has higher than national average economic inequality, child poverty rates, and percentage of nonwhite residents, making it especially promising for assessing potential socioeconomic heterogeneity in causal effects. The sample's diversity on key correlates of socioeconomic status like race, mother's education, and mother's age is shown in Table S1. The table also shows that characteristics associated with disadvantage are slightly over-represented in our estimation sample in comparison to all Florida births, which predominantly reflects the fact that families with adverse characteristics are more likely to enroll children in public school and less likely to migrate out of Florida.

The measures of socioeconomic status used in the paper are derived from birth records: mother's educational attainment; the median income of the zip code of the mother's residence; and two principal-components based composite measures of multiple SES inputs. Maternal education is grouped into three categories: high school dropout (less than 12 years of education), high school graduate (12 to 15 years of education) and college graduate (16 or more years of education).

Income assigns the median income value based on 2000 U.S. Census for each zip code of parental primary residence as indicated in birth records. The primary composite measure includes these two measures along with family structure (mother and father married; parents unmarried but father listed on birth certificate; no father listed [reference category]) and whether the birth was paid for by Medicaid. Maternal education in years is used. Since zip code income is measured at different level (zip-code) than other SES inputs (individual) we have also explored PCA analysis excluding median income.

The primary academic achievement variables used are the reading and mathematics scores from the Florida Comprehensive Assessment Test (FCAT), which was administered annually throughout Florida public schools over our study period. Published correlations between tests designed to measure general cognitive ability (i.e., "IQ", *g*) and standardized achievement test scores vary but are often around .7 (*40-41*), with lower correlations observed when short or limited-domain IQ tests are used or when academic achievement is measured from grade-point average or teacher assessment rather than test.

We standardize results for both FCAT tests by grade, year, and sex, to have a mean of zero and standard deviation of one in the overall population. This means that the mean score in our linked sample will be above zero because children of migrants into Florida have lower achievement than children born in Florida. We averaged scores across multiple grades to reduce measurement error. Stanford achievement tests were also administered to Florida students in school years 2000/2001 to 2006/2007, and we include results from these as Supporting Information Figures S4 to S9, S12 to S13, S20 to S21 and S24 to S25. Because of the restriction on the years when the test was administered we can only perform the analysis for grades 3 to 5.

We use two estimation strategies which are described in more detail in Supporting Information Technical Appendix. First, we divide pairs into SES subgroups and we compute between-pair and within-pair variances for each group using mixed-effects linear regression estimated with maximum likelihood where within-individual across grades errors are assumed to have autoregressive structure of order one. Random effects are structured at twin/sibling pair and individual level. We also report the intraclass correlations, which are computed as the ratio of between pair variation to sum of within and between pair variation.

Second, we employ a model of continuous moderation, as described by Tucker-Drob and Bates (16). This model of phenotype variation starts with the A (additive genetic), C (shared environment), E (non-shared environment) parameters of the classic twin study model, and adds a parameter M to separate the variance accounted for by the potential moderating variable (in our case, the SES measure). Then it adds interaction parameters A’, C’, E’, so that, for example, A’ = A*SES. Identifying these parameters requires assuming the average relatedness of same-sex twin pairs, which are a combination of MZ (r=1) and DZ (r=.5) twins. In the main analysis we use relatedness of 0.76 (grades 3 to 5) and 0.77 (grades 6 to 8) derived based on our data, but also conduct sensitivity estimates over a range of values between 0.700 and 0.800.

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Figure legends:

Figure 1: This figure plots means of gender-standardized test scores in mathematics and reading over maternal years of education (separated by age group and test type). Sample includes all twin pairs and closely-spaced sibling pairs with available test scores. Closely-spaced sibling pair is defined as two siblings having the same mother for whom the distance in months between births is the smallest among births to this mother between 1994 and 2002. N is 299,426 children (24,640 twins and 274,786 singletons) and 1,796,532 children-year observations.

Figure 2: This figure plots intraclass correlation coefficients and 95% confidence intervals for same-sex male (SS-M), same-sex female (SS-F) and opposite-sex (OS) samples of twins (Twin) and closely spaced siblings (Sib). Closely-spaced sibling pair is defined as two siblings having the same mother for whom the distance in months between births is the smallest among births to this mother between 1994 and 2002. Intraclass correlation coefficients are based on multilevel mixed-effects linear regression estimated with maximum likelihood where within-individual across grades errors are assumed to have autoregressive structure of order one. Random effects are structured at twin/sibling pair and individual level. Intraclass correlation is computed as ratio of between-pair variation to sum of within- and between-pair variation. N is 299,426 children (24,640 twins and 274,786 singletons) and 1,796,532 children-year observations.

Figure 3: These figures present estimates and 95% confidence intervals of between- and within-pair variation for same-sex and opposite-sex twin pairs and test scores in mathematics and reading assessed in grades 3 to 5 or 6 to 8 and split by years of maternal education. The variances are obtained using multilevel mixed-effects linear regression estimated with maximum likelihood where within-individual across grades errors are assumed to have autoregressive structure of order one. Random effects are structured at twin pair and individual level. N is 24,640 twins and 147,828 children-year observations.

Figure 4: These figures present estimates of intraclass correlation coefficients for same-sex and opposite-sex pairs of twins and siblings based on test scores in mathematics and reading assessed in grades 3 to 5 or 6 to 8 and split by years of maternal education. Siblings are defined as two individuals having the same mother for whom the distance in months between births is the smallest among births to this mother between 1994 and 2002. The intraclass correlations are based on multilevel mixed-effects linear regression estimated with maximum likelihood where within-individual across grades errors are assumed to have autoregressive structure of order one. Random effects are structured at twin/sibling pair and individual level. Intraclass correlation is computed as ratio of between pair variation to sum of within and between pair variation. N is 299,426 children (24,640 twins and 274,786 singletons) and 1,796,532 children-year observations.

Table 1. Modified ACE variance components model

Test	Grades	A (additive genetic)	M (SES measure)	C (common environment)	E (non-shared environment)	A' (genetic x SES)	95% CI for A' Lower	95% CI for A' Upper	N
Math	3 to 5	0.590	0.143	0.052	0.209	-0.101	-0.120	-0.082	34,432
Reading	3 to 5	0.619	0.149	0.003	0.224	-0.030	-0.073	0.013	
Math	6 to 8	0.628	0.169	0.000	0.181	-0.050	-0.110	0.010	21,653
Reading	6 to 8	0.594	0.166	0.017	0.197	-0.077	-0.130	-0.023	

Note: This table is based on variance components models used in Purcell (29) and Tucker-Drob and Bates (16). The first two models (grades 3 to 5) use relatedness value of 0.76 while the latter two models (grades 6 to 8) use relatedness value of 0.77. Relatedness is defined as (N-M)/N+0.5(M/N) where N is number of same-sex twins and M is number of opposite-sex twins. First two columns list test and test grades. Subsequent columns present variances due to additive genetic effects (A); socioeconomic status measure which in our case is years of maternal education at birth (M); shared environment (C) and non-shared environment (E). A' is a moderator term of interest for additive genetic effects displayed together with lower and upper bounds of 95% confidence intervals in the following two columns. Scarr-Rowe hypothesis requires A' to be positive and statistically significant. Last column presents sample sizes used in estimation.

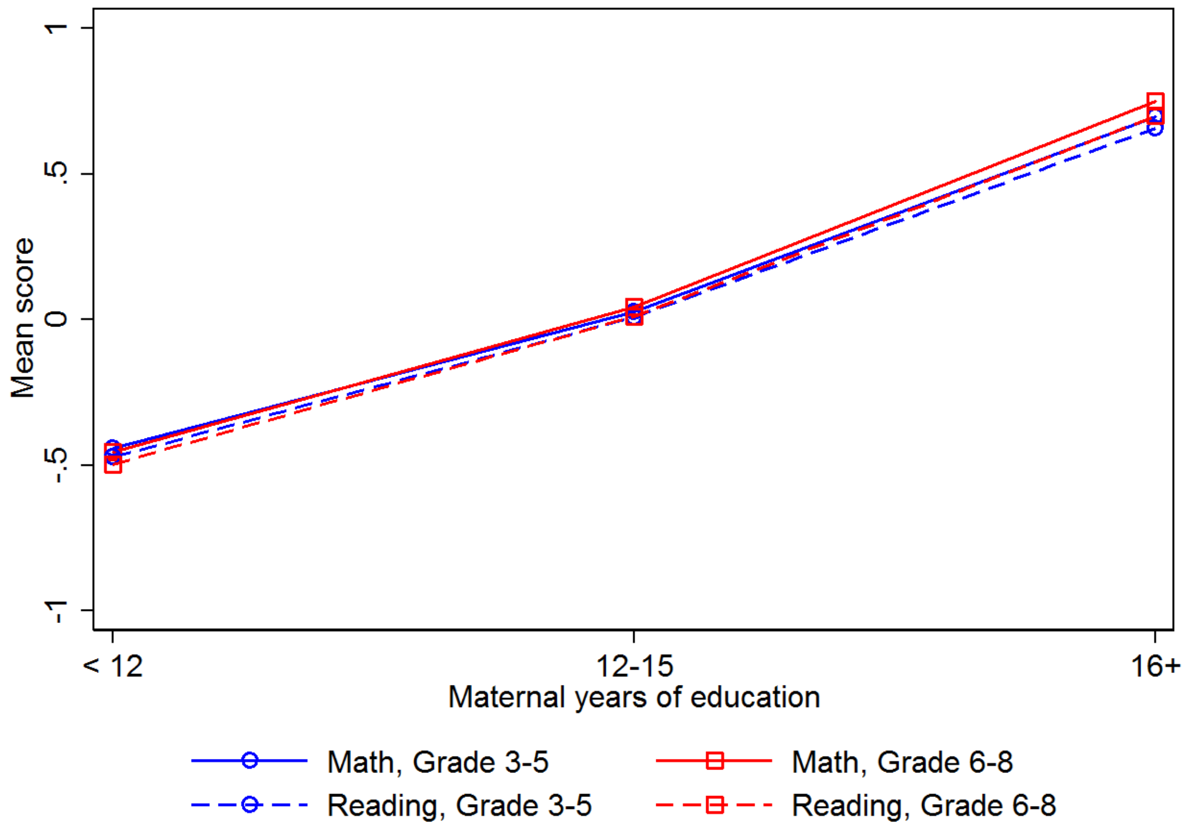


Fig. 1. Maternal years of education and average achievement test score for combined twin and sibling pairs sample.

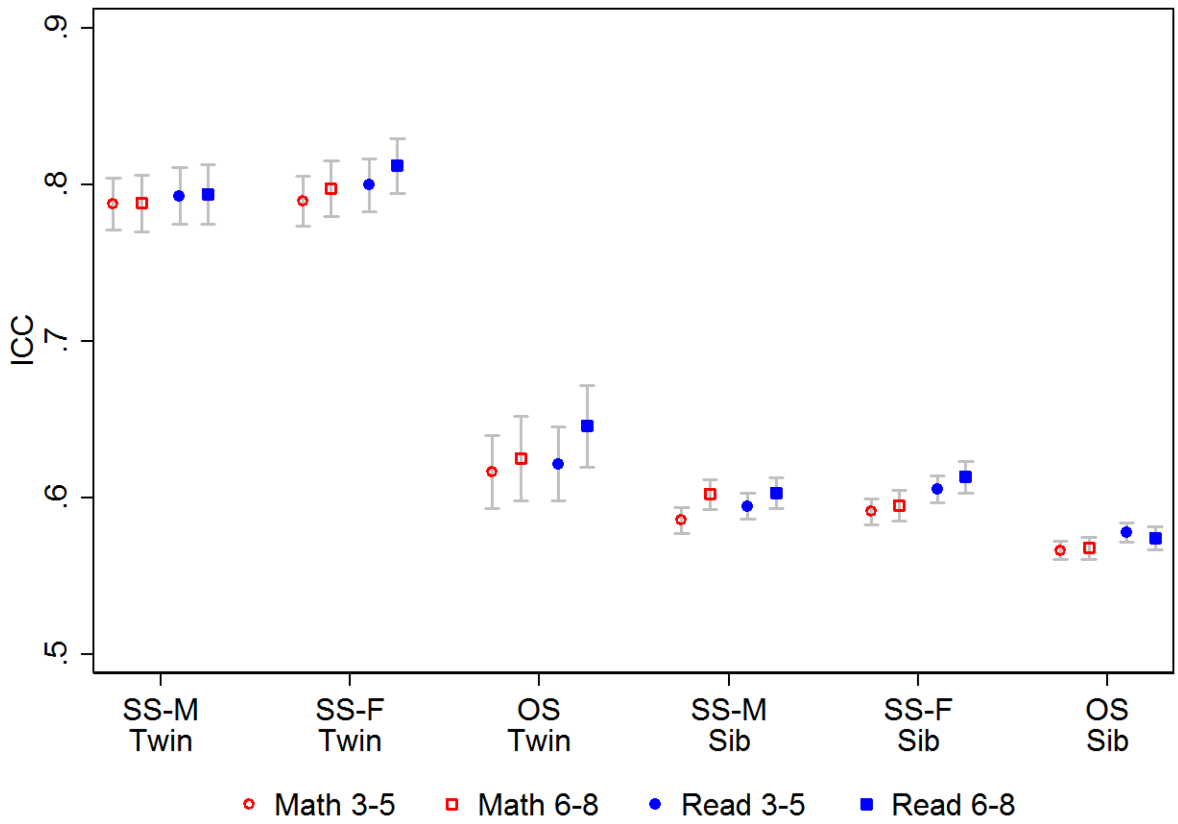


Fig. 2. Intraclass correlations for different twin and sibling pair types. Math and reading achievement tests for younger (grade 3-5) and older (grade 6-8) children.

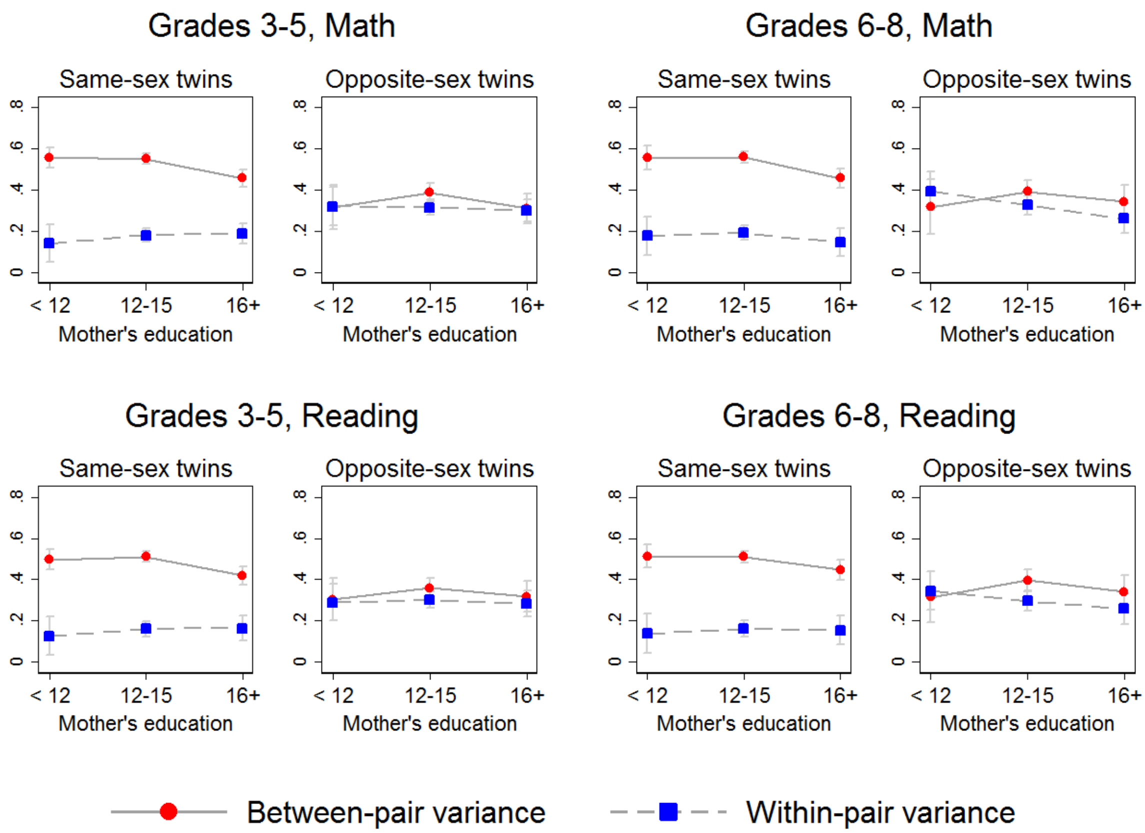


Fig. 3. Between- and within-pair variance in achievement test scores for same-sex and opposite-sex twins.

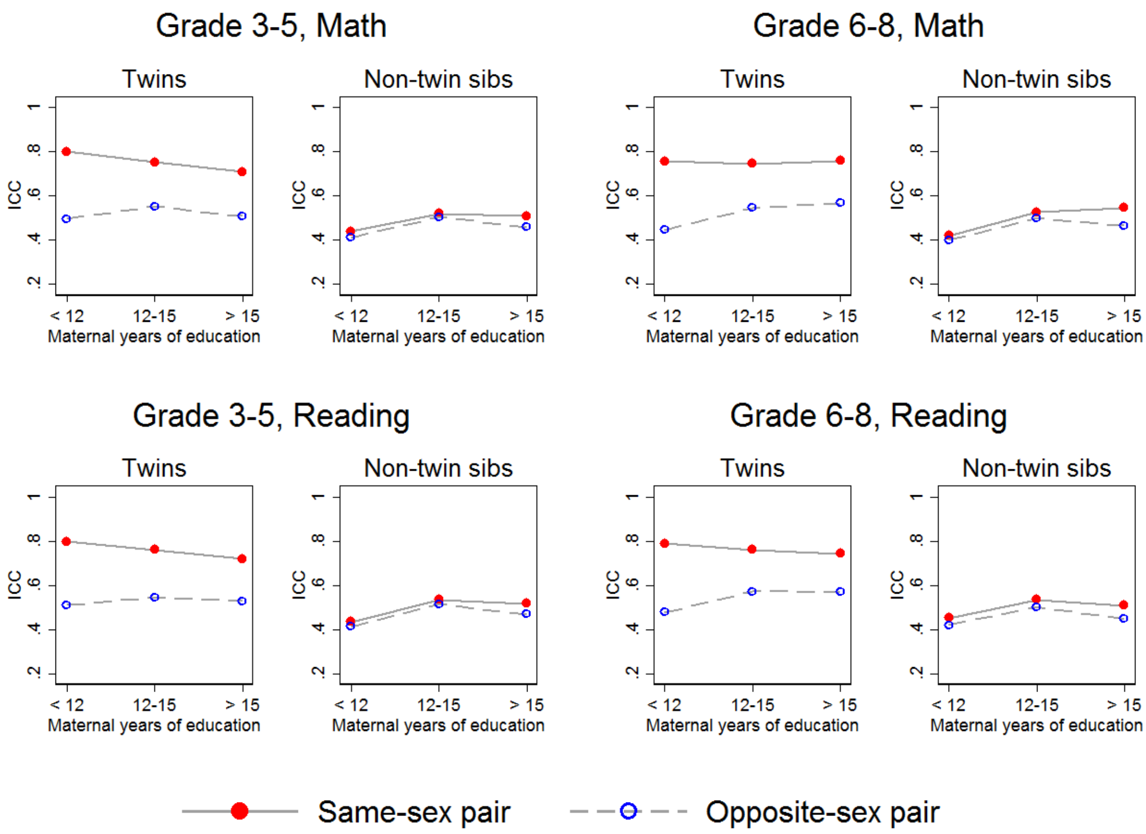


Fig. 4. Intraclass correlations for same-sex and opposite-sex twin and non-twin sibling pairs.

Supporting Information:

Technical Appendix

Intraclass correlations

The intraclass correlations presented in Figure 2 are based on multilevel mixed-effects linear regressions fitted using maximum likelihood. The models include three levels: multiple years of test scores (either grades 3 to 5 or grades 6 to 8) are nested within individuals, and individuals are nested within twin or sibling pairs. Accordingly, the analysis includes random intercepts for both an individual and a pair. The regression takes the following form:

$$Y_{gij} = \alpha_{000} + \mu_{00j} + \tau_{0ij} + \varepsilon_{gij} \tag{1}$$

with subscripts g used for grade, i for individual, and j for pair. In the regression, α_{000} is a fixed intercept representing grand mean; μ_{00j} is pair specific random intercept (pair deviation from fixed intercept); τ_{0ij} is an individual specific random intercept (individual deviation from pair predicted outcome); ε_{gij} is a residual (grade specific deviation from individual predicted outcome). Level 1 of the model is $Y_{gij} = \beta_{0ij} + \varepsilon_{gij}$; level 2 is $\beta_{0ij} = c_{00j} + \tau_{0ij}$; and level 3 is $c_{00j} = \alpha_{000} + \mu_{00j}$. We model the residuals to have autoregressive structure of order one. We fit separately 2×2×2×3 combinations:

- Two outcomes: reading and math
- Two grade levels: 3 to 5 or 6 to 8
- Two pair types: twins and non-twin siblings
- Three gender-composition types: male-male, female-female, male-female

This model allows us to compute within-person, within-pair and between pair variances for each of the 24 combinations listed above. Namely, level 1 variance (within person) is V_e; level 2 variance (within pair) is $V_{\tau 0}$; and level 3 variance (between pair) is $V_{\mu 00}$. Once we obtain the three variances from the model we can compute total pair variance $V_{total} = V_{\tau 0} + V_{\mu 00}$, which is just a sum of within and between pair variances. The intraclass correlation is then a ratio of between pair variance to total pair variance i.e. $ICC = \frac{V_{\mu 00}}{V_{total}}$.

Variance decomposition

We use the same method and exactly the same equation for the variance decomposition shown in Figures 3 and 4, with one specific modification. Namely, we compute variances for 2×2×2×2×3 groups:

- Two outcomes: reading and math
- Two grade levels: 3 to 5 and 6 to 8

- Two gender composition types: same-sex and opposite-sex
- Two pair types: twins and non-twin siblings
- Three levels of SES: low, medium, high

For the SES levels we repeat the analysis separately for maternal education (high school dropout, high school graduate, college graduate), zip code income terciles, and PCA'ed SES index terciles.

In Figure 3 we directly plot between and within variances obtained from the model for the twin sample, which yields 3x2x2x2x2 = 48 estimates.

In Figure 4 we compute ICCs for each SES level, pair type, outcome, grade level and sex composition, which again yields 48 estimates. ICCs are computed as a ratio of between pair variance to total pair variance for each of the groups.

We compute ICCs and perform variance decomposition using Stata, and the code is available online.

ACE model with continuous moderator

The standard ACE model decomposes genetic phenotype into three factors: additive genetic factors (A), common environment factors (C), and specific environmental factors (E). It can be written mathematically as $V_p = V_A + V_C + V_E$, where V_p is a total variance of the trait and the three linearly additive variances represent factors A, C and E. This model implies that $V_A + V_C + V_E = 1$, and heritability is defined as $H = \frac{V_A}{V_p}$.

In our particular case, we are seeking to understand whether genetic influence (A) is moderated by socioeconomic status of family (SES moderator M). Since we are interested in the interactions with childhood conditions, we expand the model to include A^0, C^0 and E^0 components where $A^0 = A \times M$; $C^0 = C \times M$; $E^0 = E \times M$. Central to our interest is an interaction term A^0 that represents gene $\times$ SES interaction. We use two continuous SES moderators in this analysis: maternal years of education and PCA'ed SES index. Thus, the variance in expanded model changes to $V_{p|M} = (A + A^0)^2 + (C + C^0)^2 + (E + E^0)^2$, and the standardization condition takes a form of $\frac{(A+A^0)^2}{V_{p|M}} + \frac{(C+C^0)^2}{V_{p|M}} + \frac{(E+E^0)^2}{V_{p|M}} = 1$.

Identification of parameters for this model with twin data usually has used information on zygosity of twins, relying on the fact that monozygotic twins (MZ) share all their genes, while dizygotic twins (DZ) share on average half of their genes by descent. Thus, for MZ twins the observed covariance between twins equals $V_A + V_C$ while for DZ twins this covariance is $0.5 \cdot V_A + V_C$. Similarly when conditioning on continuous moderator we simply replace V_A and V_C with $(A + A^0)^2$ and $(C + C^0)^2$, respectively.

In the absence of information on zygosity, we use the observed gender composition of twin pair as a proxy to fit the model whose results are shown in Table 1. This is possible because all opposite-sex twin pairs are dizygotic (DZ), while same-sex twin pairs are a mix of dizygotic (DZ) and monozygotic (MZ) phenotypes. We standardize test scores within sex to remove any mean differences between sexes.

In order to proceed with modeling, however, we need a value for rSS which is genetic relatedness of the same-sex twin group. It can be estimated from $rSS = \frac{N-M}{N} + 0.5\frac{M}{N}$, where N is the number of same-sex twins in the sample and M is the number of opposite-sex twins in the sample. The first right-hand side term is a proportion of monozygotic (MZ) twins in the group, while the latter is a proportion of dizygotic (DZ) twins (multiplied by their relatedness of .5). Given that same-sex twins are often composed of about equal numbers of MZ and DZ twins, .75 is sometimes used as an approximation of rSS. We compute rSS directly from our data, and in the main sample that yields a value of 0.76 in grades 3 to 5 and value of 0.77 in grades 6 to 8. We test the robustness of the results for alternative values of rSS: 0.700, 0.725, 0.750, 0.775, 0.800. Based on this we run 2×2×6 models using twin data:

- Two outcomes: reading and math
- Two grade levels: 3 to 5 and 6 to 8
- Six values for rSS assumption

We compute these models using MPlus, and the code is available online.

Figures and tables

Table S1: Demographic characteristics of mothers

Characteristic	(1) All	(2) Matched to school records	(3) Final twin sample	(4) Final sibling sample
	Births 1994-2002			
African-American	21.9	24.1	25.6	30.7
Hispanic	23.8	24.2	18.0	25.2
Immigrant	24.0	23.4	18.0	22.2
Married	65.2	62.4	68.0	62.2
HS dropout	20.1	21.8	15.2	25.4
College graduate	21.3	18.0	24.1	18.4
Age 21 or below	21.4	23.2	14.5	24.1
Age 37 or above	7.5	7.1	10.7	4.8
N	1,636,968	1,312,345	24,640	274,786

Notes: The first column presents fractions in total population of children born in Florida between 1994 and 2002. The second column presents fractions in total population of children born between 1994 and 2002 linked to Florida school records. The third column presents fractions in final twin sample used in the empirical analysis. The fourth column presents fractions in final sibling sample used in the analysis.

Table S2: Alternative variance components model. Moderator: Maternal years of education

Test	Grades	A (additive genetic)	M (SES measure)	C (common environment)	E (non-shared environment)	A' (genetic x SES)	95% CI for A'		C' (common env. x SES)	95% CI for C'		E' (non-shared env. x SES)	95% CI for E'		N
							Lower	Upper		Lower	Upper		Lower	Upper	
Math	3 to 5	0.590	0.143	0.052	0.209	-0.101	-0.120	-0.082	0.118	0.086	0.150	0.030	0.020	0.040	34.432
Reading	3 to 5	0.619	0.149	0.003	0.224	-0.030	-0.073	0.013	0.151	0.126	0.175	0.016	-0.005	0.037	
Math	6 to 8	0.628	0.169	0.000	0.181	-0.050	-0.110	0.010	-0.173	-0.206	-0.139	-0.018	-0.048	0.012	21,653
Reading	6 to 8	0.594	0.166	0.017	0.197	-0.077	-0.130	-0.023	0.166	0.119	0.214	0.036	0.012	0.060	

Notes: This table is based on variance components models used in Purcell (29) and Tucker-Drob and Bates (16). Column (1) lists a test - either mathematics or reading while column (2) lists test grades. The first two models (grades 3 to 5) use relatedness value of 0.76 while the latter two models (grades 6 to 8) use relatedness value of 0.77. Relatedness is defined as $R_{SS} = \frac{N-M}{N} + 0.5\frac{M}{N}$ where N is number of same-sex twins and M is number of opposite-sex twins. Subsequent columns present variances due to additive genetic effects (A; column 3); socioeconomic status measure which in this case is years of maternal education at birth (M ; column 4); variances due to shared environment (C; column 5) and non-shared environment (E; column 6). Columns (7) to (9) present a moderator term of interest for additive genetic effects (A^0) with 95% confidence interval. Columns (10) to (12) present a moderator term for shared environment (C^0) with 95% confidence interval. Columns (13) to (15) present moderator term for non-shared environment (E^0) with 95% confidence interval. Column (16) presents sample sizes used in estimation. Scarr-Rowe hypothesis requires estimate in column (7) to be positive and statistically significant.

Table S3: Robustness of alternative variance components model. Moderator: Maternal years of education

(1) Test	(2) R_{SS}	(3) Grades	(4) A (additive genetic)	(5) M (SES measure)	(6) C (common environment)	(7) E (non-sh. environment)	(8) A' (genetic x SES)	(9) 95% CI for A' Lower	(10) 95% CI for A' Upper	(11) C' (common env. X SES)	(12) 95% CI for C' Lower	(13) 95% CI for C' Upper	(14) E' (non-sh. env. X SES)	(15) 95% CI for E' Lower	(16) 95% CI for E' Upper	(17) N
Math		3 to 5	0.706	0.144	0.004	0.142	-0.069	-0.094	-0.044	0.141	0.113	0.170	0.030	0.010	0.049	34,432
Reading	[illegible]	3 to 5	0.674	0.148	0.001	0.174	-0.037	-0.061	-0.012	0.143	0.118	0.169	0.026	0.008	0.044	
Math		6 to 8	0.691	0.168	0.000	0.123	-0.052	-0.083	-0.020	-0.164	-0.195	-0.132	-0.012	-0.038	0.015	21,653
Reading		6 to 8	0.674	0.166	0.001	0.136	-0.049	-0.082	-0.016	0.173	0.144	0.202	0.037	0.010	0.064	
Math		3 to 5	0.669	0.144	0.014	0.167	-0.081	-0.107	-0.054	0.137	0.104	0.169	0.030	0.014	0.047	34,432
Reading	[illegible]	3 to 5	0.651	0.148	0.001	0.195	-0.036	-0.065	-0.007	0.146	0.121	0.171	0.022	0.004	0.041	
Math		6 to 8	0.667	0.168	0.000	0.144	-0.051	-0.087	-0.015	-0.167	-0.198	-0.136	-0.014	-0.040	0.011	21,653
Reading		6 to 8	0.651	0.166	0.001	0.158	-0.052	-0.092	-0.012	0.175	0.145	0.205	0.033	0.006	0.060	
Math		3 to 5	0.613	0.143	0.040	0.197	-0.096	-0.117	-0.075	0.123	0.090	0.157	0.031	0.020	0.042	34,432
Reading	[illegible]	3 to 5	0.629	0.148	0.002	0.215	-0.033	-0.071	0.005	0.149	0.125	0.174	0.018	-0.002	0.038	
Math		6 to 8	0.645	0.168	0.000	0.166	-0.050	-0.095	-0.006	-0.170	-0.202	-0.138	-0.017	-0.043	0.010	21,653
Reading		6 to 8	0.626	0.166	0.004	0.179	-0.059	-0.111	-0.008	0.175	0.139	0.210	0.032	0.004	0.060	
Math		3 to 5	0.557	0.143	0.070	0.226	-0.106	-0.123	-0.089	0.110	0.080	0.141	0.028	0.019	0.037	34,432
Read	[illegible]	3 to 5	0.601	0.149	0.008	0.237	-0.020	-0.067	0.026	0.153	0.129	0.177	0.011	-0.010	0.032	
Math		6 to 8	0.623	0.169	0.000	0.185	-0.049	-0.116	0.018	-0.174	-0.208	-0.139	-0.019	-0.051	0.013	21,653
Reading		6 to 8	0.581	0.165	0.024	0.203	-0.083	-0.131	-0.035	0.162	0.113	0.210	0.037	0.017	0.058	
Math		3 to 5	0.507	0.142	0.096	0.250	-0.112	-0.128	-0.096	0.101	0.073	0.129	0.024	0.016	0.032	34,432
Reading		3 to 5	0.521	0.147	0.061	0.267	-0.091	-0.109	-0.073	0.105	0.069	0.140	0.033	0.025	0.041	
Math		6 to 8	0.593	0.169	0.008	0.206	-0.027	-0.122	0.068	-0.179	-0.209	-0.150	-0.029	-0.066	0.008	21,653
Reading		6 to 8	0.518	0.164	0.063	0.230	-0.103	-0.130	-0.076	0.141	0.101	0.181	0.038	0.027	0.049	

Notes: This table is based on variance components models used in Purcell (29) and Tucker-Drob and Bates (16). Column (1) lists a test - either mathematics or reading while column (3) lists test grades. Column (2) presents assumptions regarding relatedness of same-sex twin group. For each combination of test type and grade range we test robustness to five relatedness values. The preferred relatedness values in Table 1 are 0.76 (grades 3 to 5) and 0.77 (grades 6 to 8). Relatedness is defined as $R_{SS} = \frac{N-M}{N} + 0.5\frac{M}{N}$ where N is number of same-sex twins and M is number of opposite-sex twins. Subsequent columns present variances due to additive genetic effects (A; column 4); socioeconomic status measure which in our case is years of maternal education at birth (M ; column 5); variance due to shared environment (C; column 6) and non-shared environment (E; column 7). Columns (8) to (10) present a moderator term of interest for additive genetic effects (A^0) with 95% confidence interval. Columns (11) to (13) present a moderator term for shared environment (C^0) with 95% confidence interval. Columns (14) to (16) present moderator term for non-shared environment (E^0) with 95% confidence interval. Column (17) presents sample sizes used in estimation. Scarr-Rowe hypothesis requires estimate in column (8) to be positive and statistically significant.

Table S4: Alternative variance components model. Moderator: PCA SES index (excluding zip code income)

Test	Grades	A (additive genetic)	M (SES measure)	C (common environment)	E (non-shared environment)	A' (genetic x SES)	95% CI for A' Lower	95% CI for A' Upper	C' (common env. x SES)	95% CI for C' Lower	95% CI for C' Upper	E' (non-shared env. x SES)	95% CI for E' Lower	95% CI for E' Upper	N
Math	3 to 5	0.563	0.150	0.075	0.219	-0.050	-0.071	-0.030	0.029	-0.013	0.070	-0.003	-0.015	0.008	34.270
Reading	3 to 5	0.569	0.151	0.049	0.238	-0.021	-0.041	-0.001	-0.001	-0.046	0.044	-0.002	-0.013	0.009	
Math	6 to 8	0.570	0.175	0.054	0.196	-0.030	-0.063	0.003	-0.008	-0.085	0.068	-0.039	-0.057	-0.022	[illegible]
Reading	6 to 8	0.540	0.164	0.076	0.214	-0.030	-0.059	-0.001	0.022	-0.035	0.079	0.009	-0.006	0.025	

Notes: See Table S2 for detailed notes. Socioeconomic status measure (M) used in this table is based on PCA of: maternal years of education, medicaid paid birth, parents married, father present or father absent.

Table S5: Robustness of alternative variance components model. Moderator: PCA SES index (excluding zip code income)

(1) Test	(2) R_{SS}	(3) Grades	(4) A (additive genetic)	(5) M (SES measure)	(6) C (common environment)	(7) E (non-sh. environment)	(8) A' (genetic x SES)	(9) 95% CI for A' Lower	(10) 95% CI for A' Upper	(11) C' (common env. X SES)	(12) 95% CI for C' Lower	(13) 95% CI for C' Upper	(14) E' (non-sh. env. X SES)	(15) 95% CI for E' Lower	(16) 95% CI for E' Upper	(17) N
Math		3 to 5	0.717	0.150	0.001	0.140	-0.036	-0.051	-0.021	0.006	-0.097	0.109	-0.006	-0.021	0.009	34,270
Reading		3 to 5	0.686	0.151	0.000	0.171	-0.021	-0.031	-0.012	0.000	-0.052	0.051	0.001	-0.010	0.012	
Math		6 to 8	0.702	0.175	0.000	0.118	-0.033	-0.045	-0.021	0.000	-0.105	0.105	-0.042	-0.057	-0.026	[illegible]
Reading		6 to 8	0.702	0.164	0.000	0.129	-0.019	-0.031	-0.007	0.000	-0.094	0.095	0.010	-0.006	0.025	
Math		3 to 5	0.645	0.150	0.035	0.177	-0.044	-0.062	-0.026	0.026	-0.022	0.073	-0.003	-0.017	0.011	34,270
Reading		3 to 5	0.658	0.151	0.005	0.194	-0.021	-0.033	-0.010	0.000	-0.052	0.053	0.000	-0.010	0.010	
Math		6 to 8	0.679	0.175	0.000	0.140	-0.033	-0.044	-0.021	0.000	-0.126	0.127	-0.054	-0.041	-0.027	[illegible]
Reading		6 to 8	0.645	0.164	0.024	0.162	-0.024	-0.047	-0.001	0.020	-0.051	0.092	0.011	-0.007	0.029	
Math		3 to 5	0.584	0.150	0.064	0.209	-0.049	-0.069	-0.029	0.029	-0.014	0.071	-0.003	-0.015	0.009	34,270
Reading	[illegible]	3 to 5	0.591	0.151	0.038	0.228	-0.021	-0.040	-0.003	-0.001	-0.048	0.046	-0.002	-0.013	0.010	
Math		6 to 8	0.615	0.175	0.031	0.173	-0.031	-0.062	-0.001	-0.006	-0.098	0.086	-0.040	-0.058	-0.021	[illegible]
Reading		6 to 8	0.582	0.164	0.055	0.193	-0.028	-0.056	-0.001	0.023	-0.039	0.085	0.010	-0.007	0.027	
Math		3 to 5	0.533	0.150	0.089	0.234	-0.052	-0.073	-0.031	0.028	-0.011	0.067	-0.004	-0.015	0.007	34,270
Read	[illegible]	3 to 5	0.537	0.151	0.065	0.254	-0.021	-0.042	0.000	-0.002	-0.044	0.040	-0.003	-0.014	0.008	
Math		6 to 8	0.560	0.175	0.060	0.201	-0.030	-0.063	0.004	-0.009	-0.083	0.065	-0.039	-0.056	-0.022	[illegible]
Reading		6 to 8	0.530	0.164	0.080	0.219	-0.030	-0.059	-0.001	0.022	-0.034	0.077	0.009	-0.006	0.024	
Math		3 to 5	0.489	0.150	0.110	0.256	-0.053	-0.075	-0.031	0.027	-0.010	0.063	-0.006	-0.016	0.004	34,270
Reading	[illegible]	3 to 5	0.493	0.151	0.087	0.277	-0.020	-0.043	0.002	-0.003	-0.042	0.035	-0.004	-0.014	0.006	
Math		6 to 8	0.513	0.175	0.082	0.225	-0.028	-0.063	0.006	-0.011	-0.075	0.053	-0.039	-0.054	-0.024	[illegible]
Reading		6 to 8	0.486	0.164	0.102	0.241	-0.031	-0.061	-0.001	0.020	-0.031	0.070	0.007	-0.006	0.021	

Notes: See Table S3 for detailed notes. Socioeconomic status measure (M) used in this table is based on PCA of: maternal years of education, medicaid paid birth, parents married, father present or father absent.

Table S6: Alternative variance components model. Moderator: PCA SES index (including zip code income)

Test	Grades	A (additive genetic)	M (SES measure)	C (common environment)	E (non-shared environment)	A' (genetic x SES)	95% CI for A' Lower	95% CI for A' Upper	C' (common env. x SES)	95% CI for C' Lower	95% CI for C' Upper	E' (non-shared env. x SES)	95% CI for E' Lower	95% CI for E' Upper	N
Math	3 to 5	0.573	0.166	0.049	0.219	-0.051	-0.070	-0.032	0.024	-0.020	0.068	-0.004	-0.015	0.008	32.991
Reading	3 to 5	0.567	0.168	0.032	0.240	-0.028	-0.045	-0.012	0.000	-0.042	0.043	0.000	-0.010	0.010	
Math	6 to 8	0.573	0.194	0.029	0.196	-0.034	-0.065	-0.003	-0.007	-0.102	0.089	-0.040	-0.057	-0.023	[illegible]
Reading	6 to 8	0.521	0.184	0.068	0.220	-0.028	-0.054	-0.002	0.002	-0.048	0.052	0.007	-0.007	0.022	

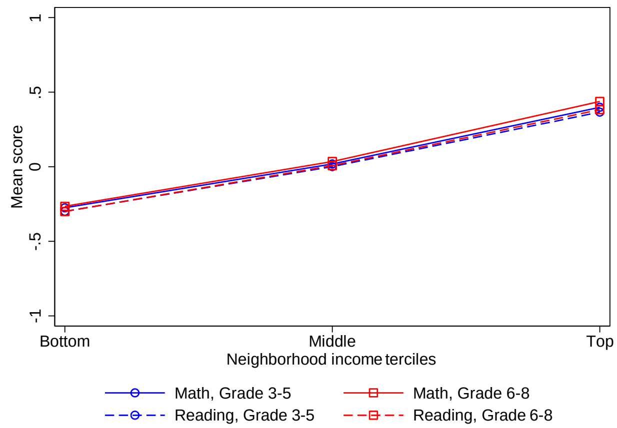
Notes: See Table S2 for detailed notes. Socioeconomic status measure (M) used in this table is based on PCA of: maternal years of education, medicaid paid birth, parents married, father present, father absent and median income at zip code of residence at the time of child's birth.

Table S7: Robustness of alternative variance components model. Moderator: PCA SES index (including zip code income)

(1) Test	(2) R_{SS}	(3) Grades	(4) A (additive genetic)	(5) M (SES measure)	(6) C (common environment)	(7) E (non-sh. environment)	(8) A' (genetic x SES)	(9) 95% CI for A' Lower	(10) 95% CI for A' Upper	(11) C' (common env. X SES)	(12) 95% CI for C' Lower	(13) 95% CI for C' Upper	(14) E' (non-sh. env. X SES)	(15) 95% CI for E' Lower	(16) 95% CI for E' Upper	(17) N
Math		3 to 5	0.692	0.166	0.000	0.151	-0.041	-0.050	-0.031	0.000	-0.060	0.060	-0.004	-0.016	0.008	32,991
Reading		3 to 5	0.659	0.168	0.000	0.181	-0.028	-0.038	-0.019	0.000	-0.045	0.045	0.004	-0.007	0.015	
Math		6 to 8	0.667	0.194	0.000	0.131	-0.036	-0.048	-0.023	0.000	-0.097	0.097	-0.042	-0.057	-0.027	[illegible]
Reading		6 to 8	0.669	0.184	0.000	0.141	-0.026	-0.038	-0.014	0.000	-0.063	0.063	0.014	-0.001	0.029	
Math		3 to 5	0.656	0.166	0.010	0.177	-0.043	-0.060	-0.027	0.015	-0.040	0.071	-0.004	-0.017	0.009	32,991
Reading		3 to 5	0.638	0.168	0.000	0.202	-0.028	-0.037	-0.018	0.000	-0.047	0.047	0.002	-0.008	0.012	
Math		6 to 8	0.646	0.194	0.000	0.151	-0.035	-0.047	-0.023	0.000	-0.110	0.110	-0.041	-0.055	-0.028	[illegible]
Reading		6 to 8	0.624	0.184	0.016	0.168	-0.027	-0.045	-0.009	0.003	-0.058	0.064	0.011	-0.004	0.027	
Math		3 to 5	0.594	0.166	0.039	0.208	-0.049	-0.068	-0.031	0.023	-0.022	0.069	-0.004	-0.016	0.008	32,991
Reading		3 to 5	0.590	0.168	0.022	0.229	-0.028	-0.043	-0.013	0.000	-0.044	0.044	0.001	-0.010	0.011	
Math		6 to 8	0.618	0.194	0.006	0.173	-0.035	-0.055	-0.015	-0.004	-0.124	0.116	-0.041	-0.056	-0.026	[illegible]
Reading		6 to 8	0.563	0.184	0.047	0.200	-0.028	-0.052	-0.004	0.003	-0.051	0.057	0.009	-0.006	0.025	
Math		3 to 5	0.543	0.166	0.064	0.234	-0.052	-0.072	-0.033	0.024	-0.017	0.065	-0.005	-0.016	0.006	32,991
Read		3 to 5	0.536	0.168	0.048	0.256	-0.029	-0.047	-0.010	0.000	-0.040	0.040	-0.001	-0.011	0.010	
Math		6 to 8	0.563	0.194	0.034	0.202	-0.034	-0.066	-0.001	-0.007	-0.098	0.084	-0.040	-0.057	-0.023	[illegible]
Reading		6 to 8	0.511	0.184	0.073	0.226	-0.028	-0.055	-0.001	0.002	-0.047	0.051	0.007	-0.007	0.021	
Math		3 to 5	0.500	0.166	0.085	0.257	-0.054	-0.075	-0.033	0.023	-0.015	0.061	-0.006	-0.016	0.004	32,991
Reading		3 to 5	0.491	0.168	0.070	0.278	-0.028	-0.048	-0.008	-0.001	-0.038	0.036	-0.002	-0.011	0.008	
Math		6 to 8	0.516	0.194	0.057	0.225	-0.033	-0.067	0.001	-0.008	-0.084	0.067	-0.040	-0.055	-0.025	[illegible]
Reading		6 to 8	0.469	0.184	0.094	0.247	-0.028	-0.056	0.000	0.001	-0.045	0.046	0.005	-0.007	0.018	

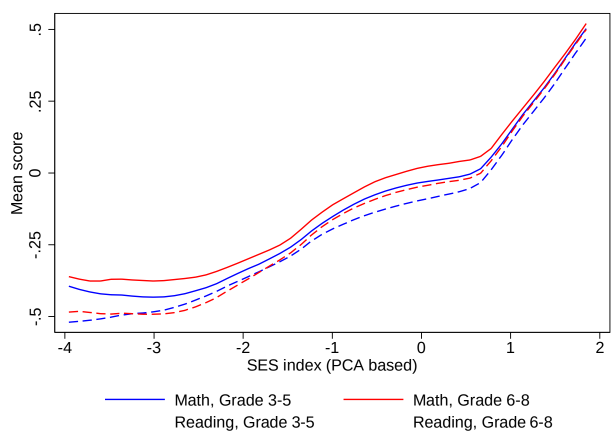
Notes: See Table S3 for detailed notes. Socioeconomic status measure (M) used in this table is based on PCA of: maternal years of education, medicaid paid birth, parents married, father present, father absent and median income at zip code of residence at the time of child's birth.

Figure S1: Neighborhood income at birth and average achievement test score for combined twin and sibling pairs sample



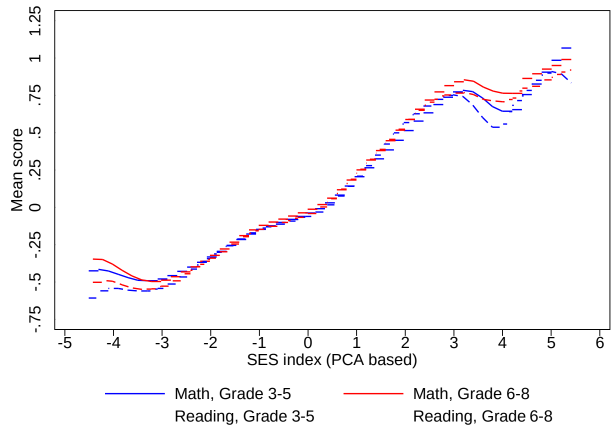
Notes: This figure plots means of gender-standardized test scores in mathematics and reading over zip-code level neighborhood income terciles at birth (separated by age group and test type). Sample includes all twin pairs and closely spaced sibling pairs with available test scores. Closely spaced sibling pair is defined as two siblings having the same mother for whom the distance in months between births is the smallest among births to this mother between 1994 and 2002.

Figure S2: SES index (PCA excluding zip code income) at birth and average achievement test score for combined twin and sibling pairs sample



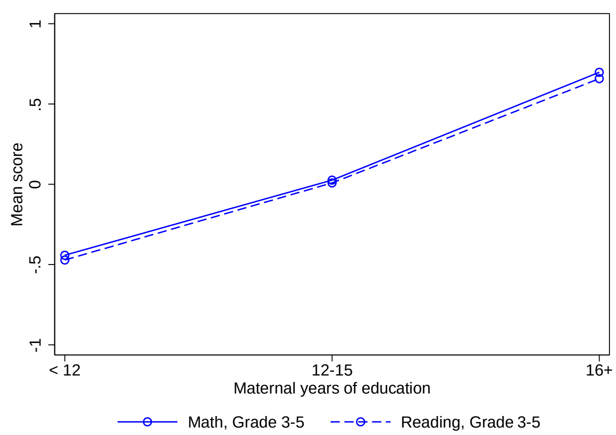
Notes: This figure plots means (smoothed polynomial) of gender-standardized test scores in mathematics and reading over SES index based on maternal years of education, medicaid paid birth, mother married, father present and father absent. Sample includes all twin pairs and closely spaced sibling pairs with available test scores. Closely spaced sibling pair is defined as two siblings having the same mother for whom the distance in months between births is the smallest among births to this mother between 1994 and 2002.

Figure S3: SES index (PCA including zip code income) at birth and average achievement test score for combined twin and sibling pairs sample



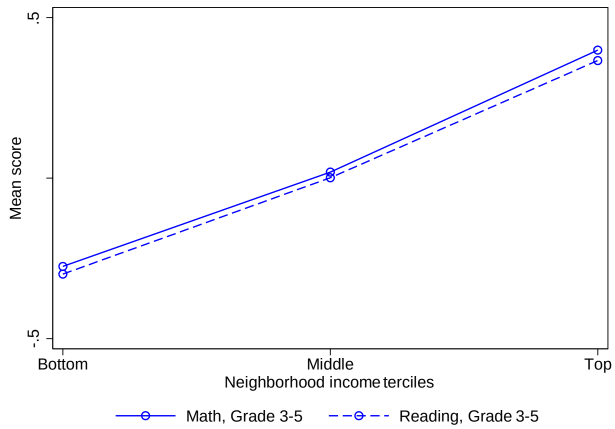
Notes: This figure plots means (smoothed polynomial) of gender-standardized test scores in mathematics and reading over SES index based on maternal years of education, medicaid paid birth, mother married, father present, father absent and median zip-code level neighborhood income at birth. Sample includes all twin pairs and closely spaced sibling pairs with available test scores. Closely spaced sibling pair is defined as two siblings having the same mother for whom the distance in months between births is the smallest among births to this mother between 1994 and 2002.

Figure S4: Maternal years of education and average Stanford achievement test score for combined twin and sibling pairs sample



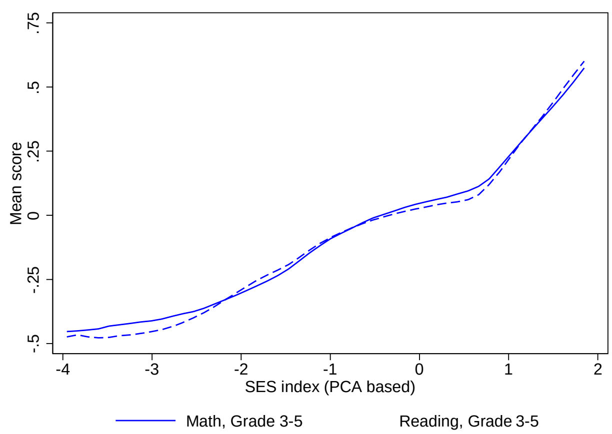
Notes: This figure plots means of gender-standardized Stanford achievement test scores in mathematics and reading over maternal years of education (separated by test type). Sample includes all twin pairs and closely spaced sibling pairs with available test scores. Closely spaced sibling pair is defined as two siblings having the same mother for whom the distance in months between births is the smallest among births to this mother between 1994 and 2002. Stanford achievement test is only available for grades 3 to 5.

Figure S5: Neighborhood income at birth and average Stanford achievement test score for combined twin and sibling pairs sample



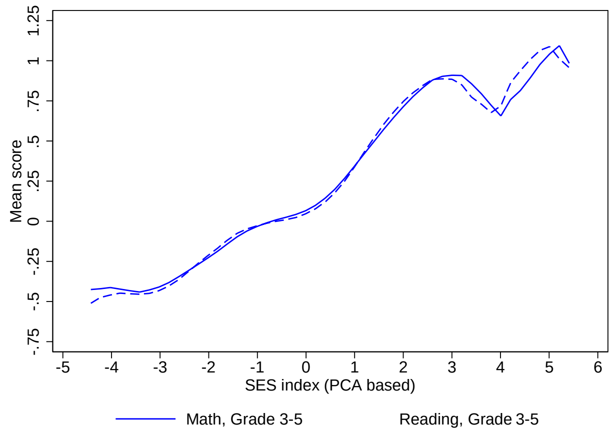
Notes: This figure plots means of gender-standardized Stanford achievement test scores in mathematics and reading over zip-code level neighborhood income terciles at birth (separated by test type). Sample includes all twin pairs and closely spaced sibling pairs with available test scores. Closely spaced sibling pair is defined as two siblings having the same mother for whom the distance in months between births is the smallest among births to this mother between 1994 and 2002. Stanford achievement test is only available for grades 3 to 5.

Figure S6: SES index (PCA excluding zip code income) at birth and average Stanford achievement test score for combined twin and sibling pairs sample



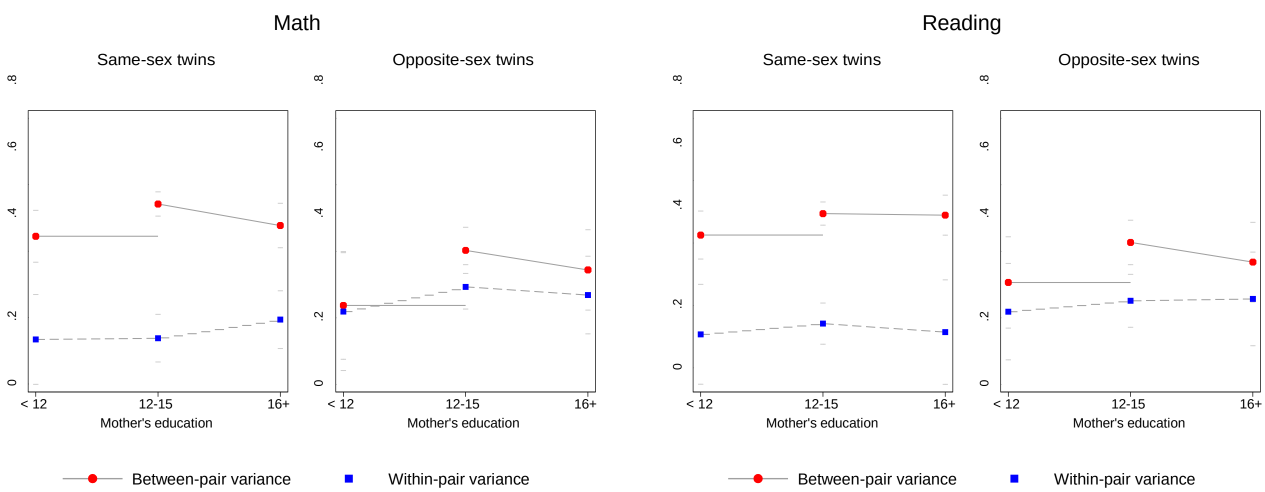
Notes: This figure plots means (smoothed polynomial) of gender-standardized Stanford achievement test scores in mathematics and reading over SES index based on maternal years of education, medicaid paid birth, mother married, father present and father absent (separated by test type). Sample includes all twin pairs and closely spaced sibling pairs with available test scores. Closely spaced sibling pair is defined as two siblings having the same mother for whom the distance in months between births is the smallest among births to this mother between 1994 and 2002. Stanford achievement test is only available for grades 3 to 5.

Figure S7: SES index (PCA including zip code income) at birth and average Stanford achievement test score for combined twin and sibling pairs sample



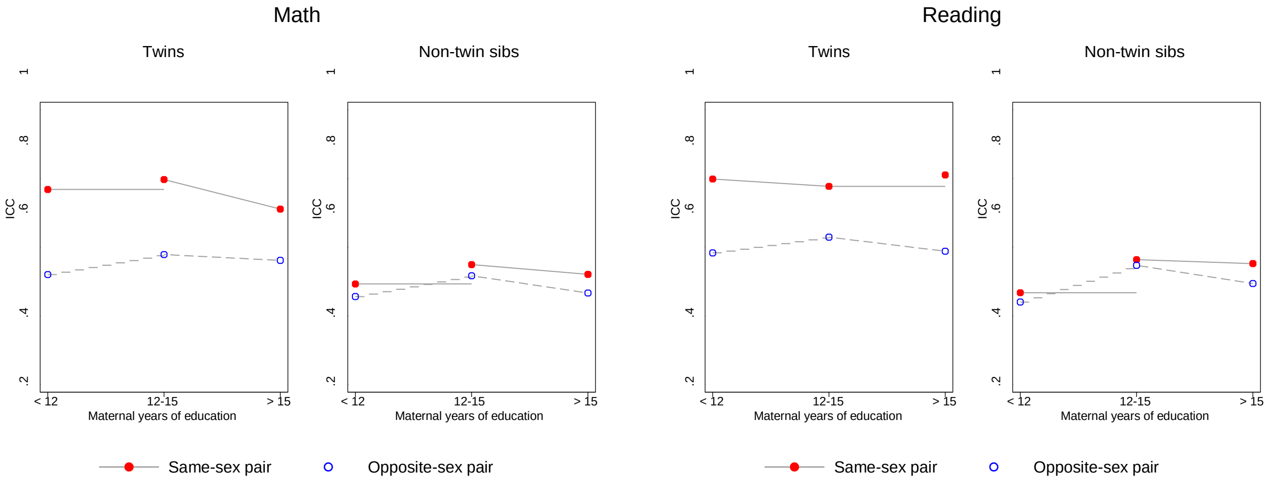
Notes: This figure plots means (smoothed polynomial) of gender-standardized Stanford achievement test scores in mathematics and reading over SES index based on maternal years of education, medicaid paid birth, mother married, father present, father absent and median zip-code level neighborhood income at birth (separated by test type). Sample includes all twin pairs and closely spaced sibling pairs with available test scores. Closely spaced sibling pair is defined as two siblings having the same mother for whom the distance in months between births is the smallest among births to this mother between 1994 and 2002. Stanford achievement test is only available for grades 3 to 5.

Figure S8: Between- and within-pair variance in Stanford achievement test for same-sex and opposite sex twins



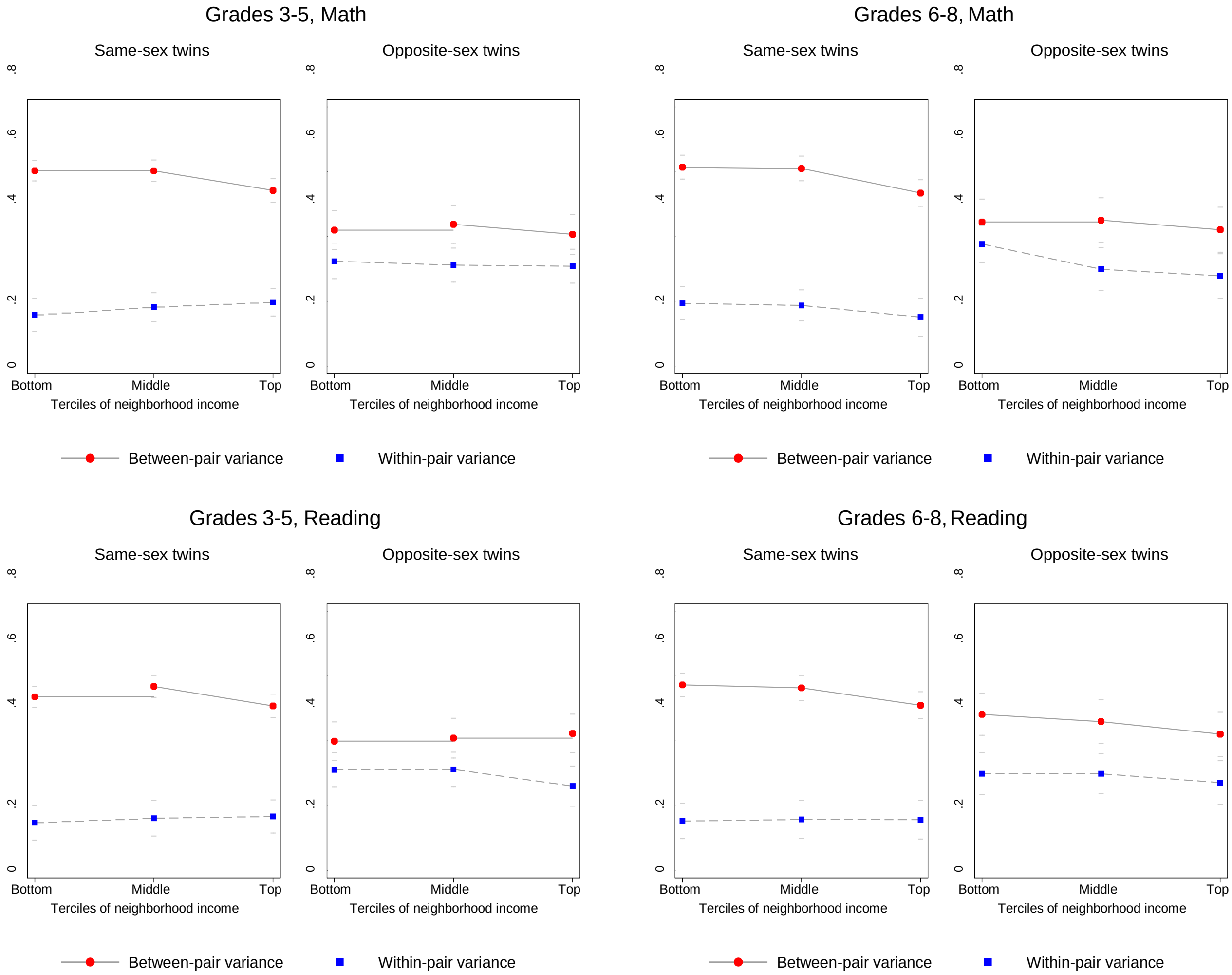
Notes: The left-hand side figures present between- and within-pair variance among same-sex and opposite-sex twins in grades 3 to 5 Stanford mathematics achievement test. The right-hand side figures present identical results for reading test. For estimation details see Figure 3.

Figure S9: Intraclass correlations for same-sex and opposite-sex twin and non-twin sibling pairs on Stanford achievement test



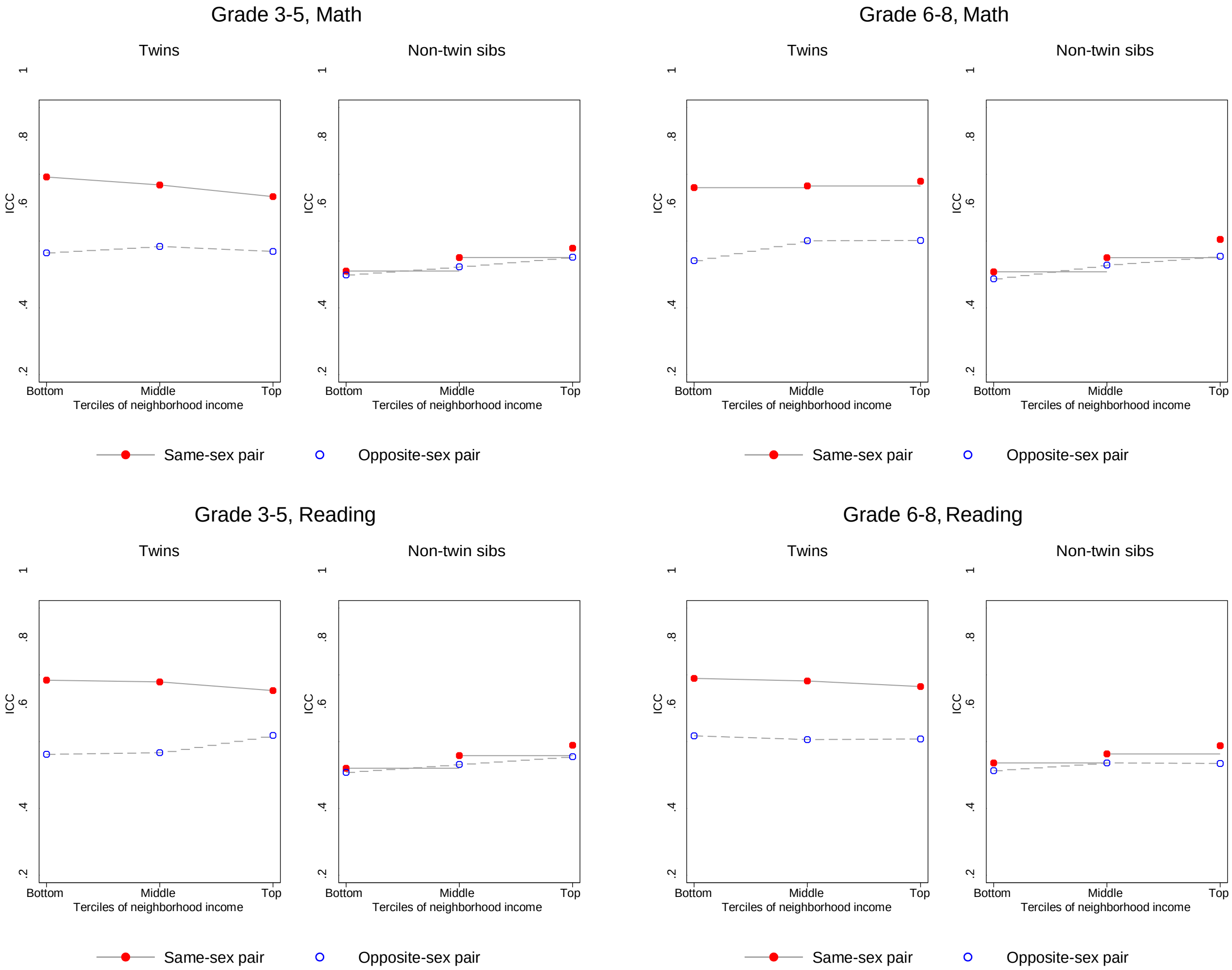
Note: The left-hand side figures present intraclass correlation coefficients among same-sex and opposite-sex pairs of twins and closely spaced siblings in grades 3 to 5 Stanford achievement test. The right-hand side figures present identical results for reading test. For estimation details see Figure 4.

Figure S10: Between- and within-pair variance in achievement test scores for same-sex and opposite-sex twins. Neighborhood income SES measure.



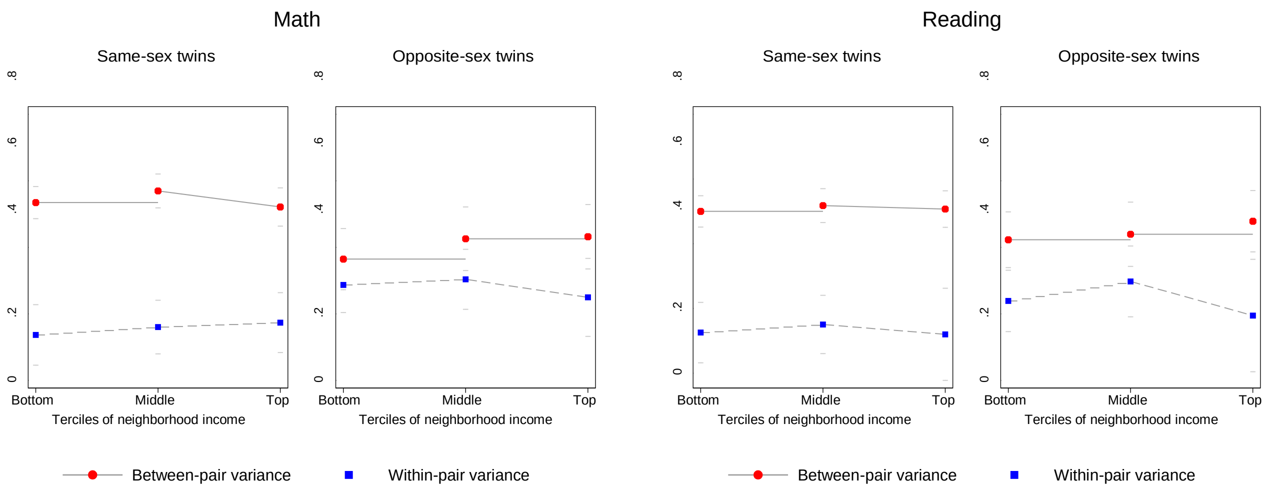
Note: The left-hand side figures present between- and within-pair variance among same-sex and opposite-sex twins in grades 3 to 5 mathematics (top) and reading (bottom) FCAT test scores. The right-hand side figures present identical results for grades 6 to 8. Socioeconomic status is measured based on zip-code level neighborhood income. For estimation details see Figure 3.

Figure S11: Intraclass correlation for same-sex and opposite-sex twin and non-twin sibling pairs. Neighborhood income SES measure.



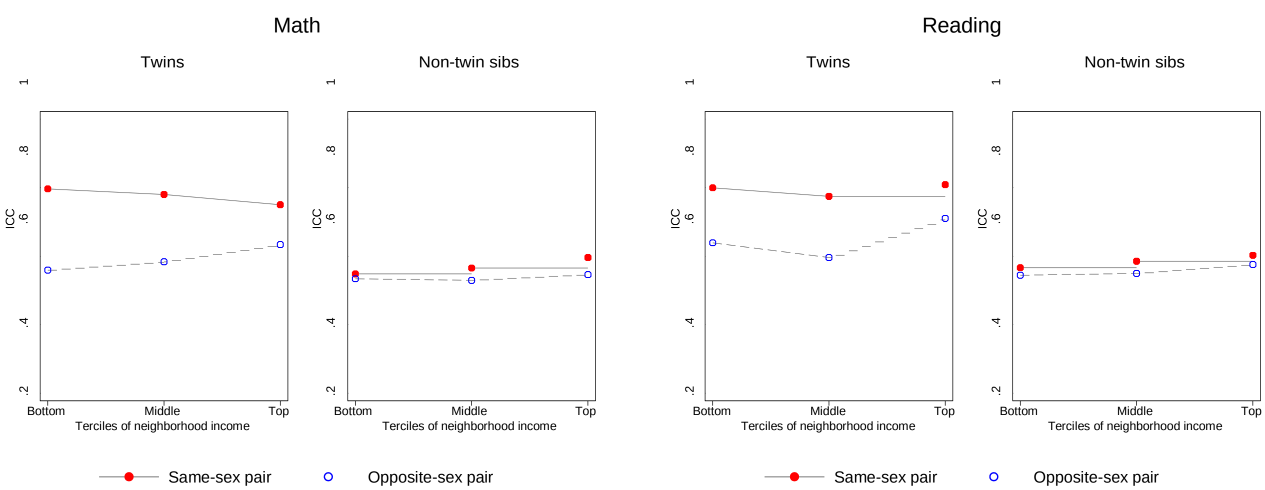
Note: The left-hand side figures present intraclass correlation coefficients among same-sex and opposite-sex pairs of twins and closely spaced siblings in grades 3 to 5 mathematics (top) and reading (bottom) FCAT test scores. The right-hand side figures present identical results for grades 6 to 8. Socioeconomic status is measured based on zip-code level neighborhood income. For estimation details see Figure 4.

Figure S12: Between- and within-pair variance in Stanford achievement test for same-sex and opposite-sex twins. Neighborhood income SES measure.



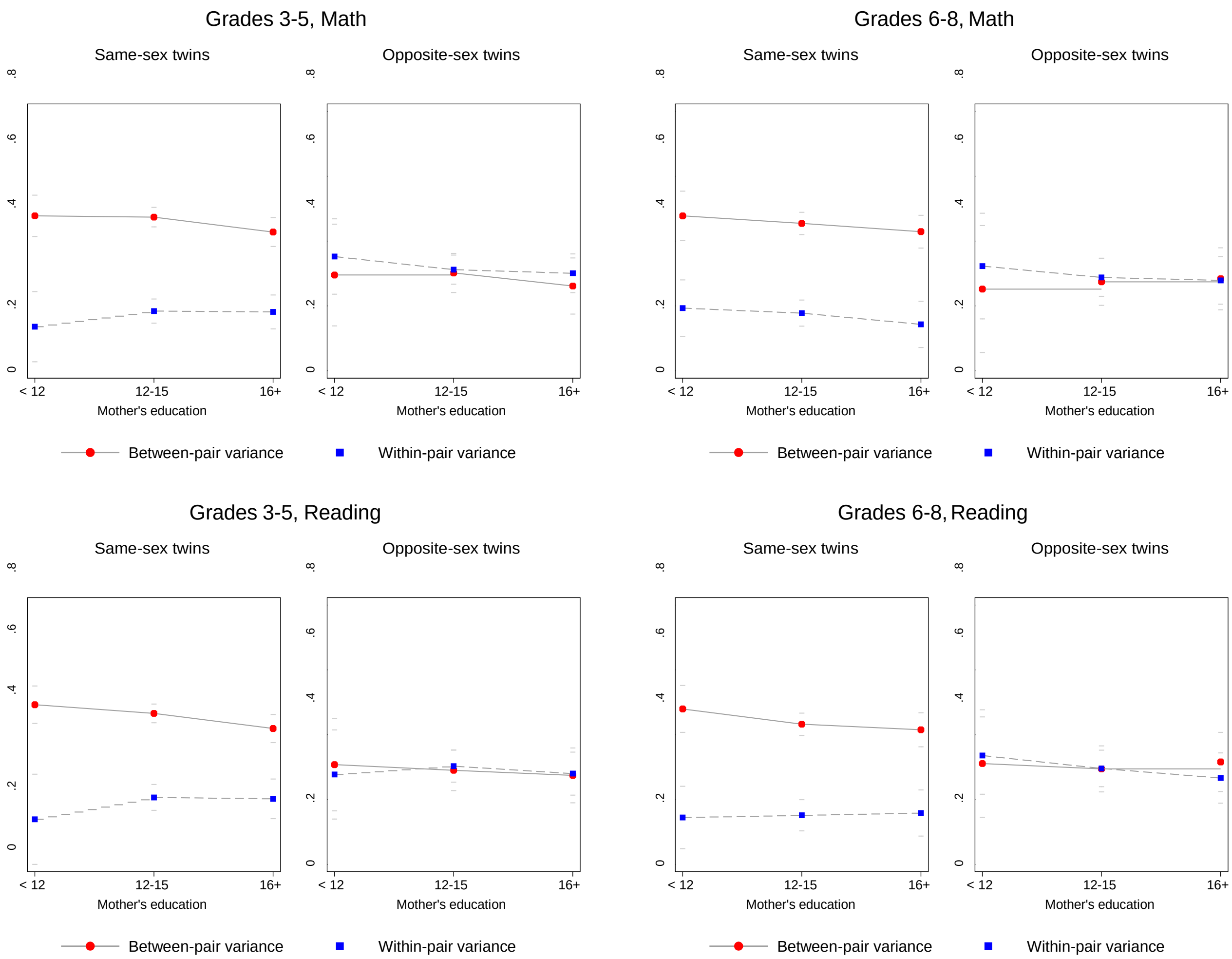
Notes: The left-hand side figures presents between- and within-pair variance among same-sex and opposite-sex twins in grades 3 to 5 Stanford mathematics achievement test. The right-hand side figures present identical results for reading test. Socioeconomic status is measured based on zip-code level neighborhood income. For estimation details see Figure 3.

Figure S13: Intraclass correlations for same-sex and opposite-sex twin and non-twin sibling pairs on Stanford achievement test. Neighborhood income SES measure.



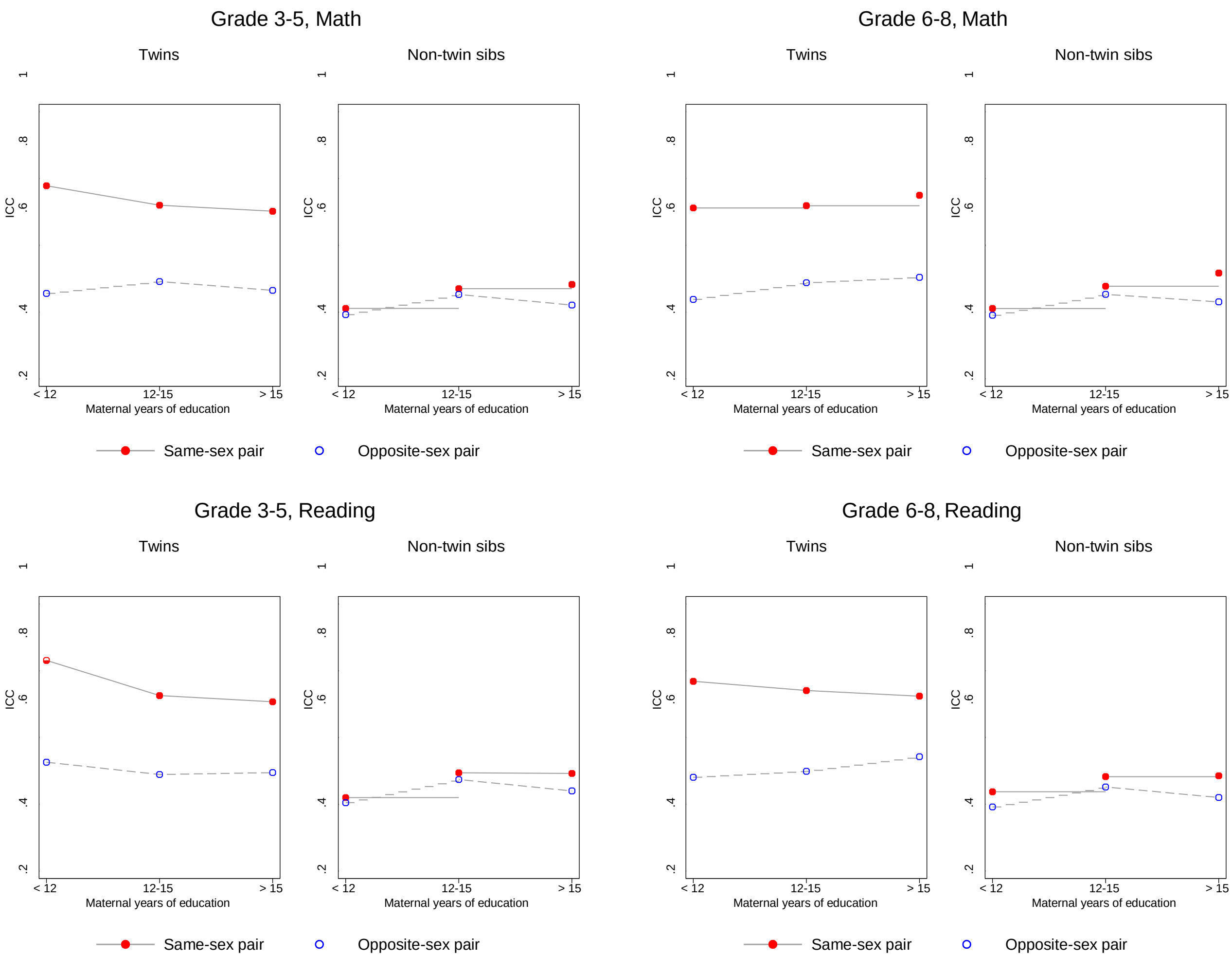
Note: The left-hand side figures presents intraclass correlations among same-sex and opposite-sex pairs of twins and non-twin siblings in grades 3 to 5 Stanford mathematics achievement test. The right-hand side figures present identical results for reading test. Socioeconomic status is measured based on zip-code level neighborhood income. For estimation details see Figure 4.

Figure S14: Between- and within-pair variance in achievement test scores for same-sex and opposite-sex twins. White mothers



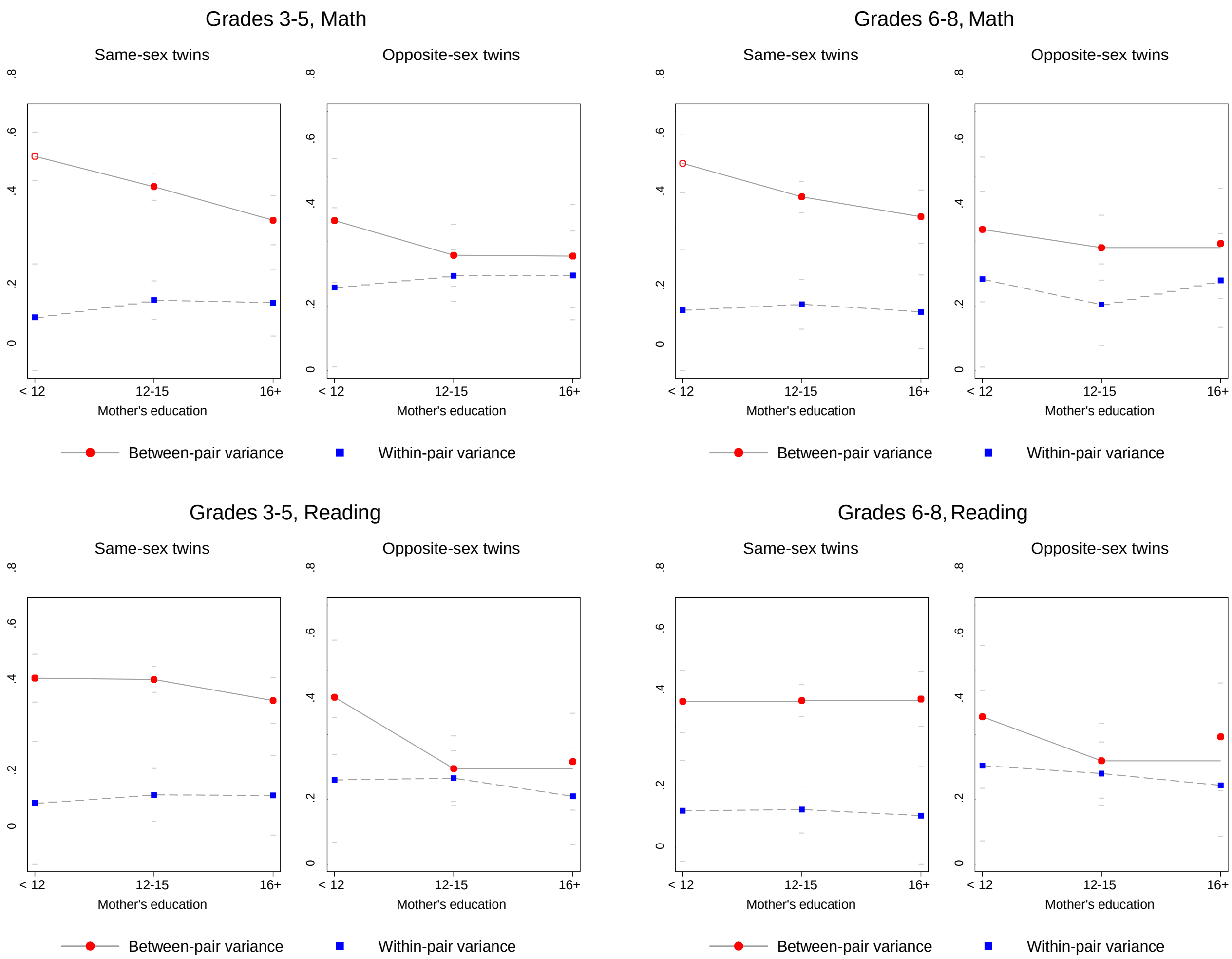
Note: The left-hand side figures present between- and within-pair variance among same-sex and opposite-sex twins in grades 3 to 5 mathematics (top) and reading (bottom) FCAT test scores. The right-hand side figures present identical results for grades 6 to 8. Socioeconomic status is measured based on maternal years of education. Sample of white mothers. For estimation details see Figure 3.

Figure S15: Intraclass correlation for same-sex and opposite-sex twin and non-twin sibling pairs. White mothers.



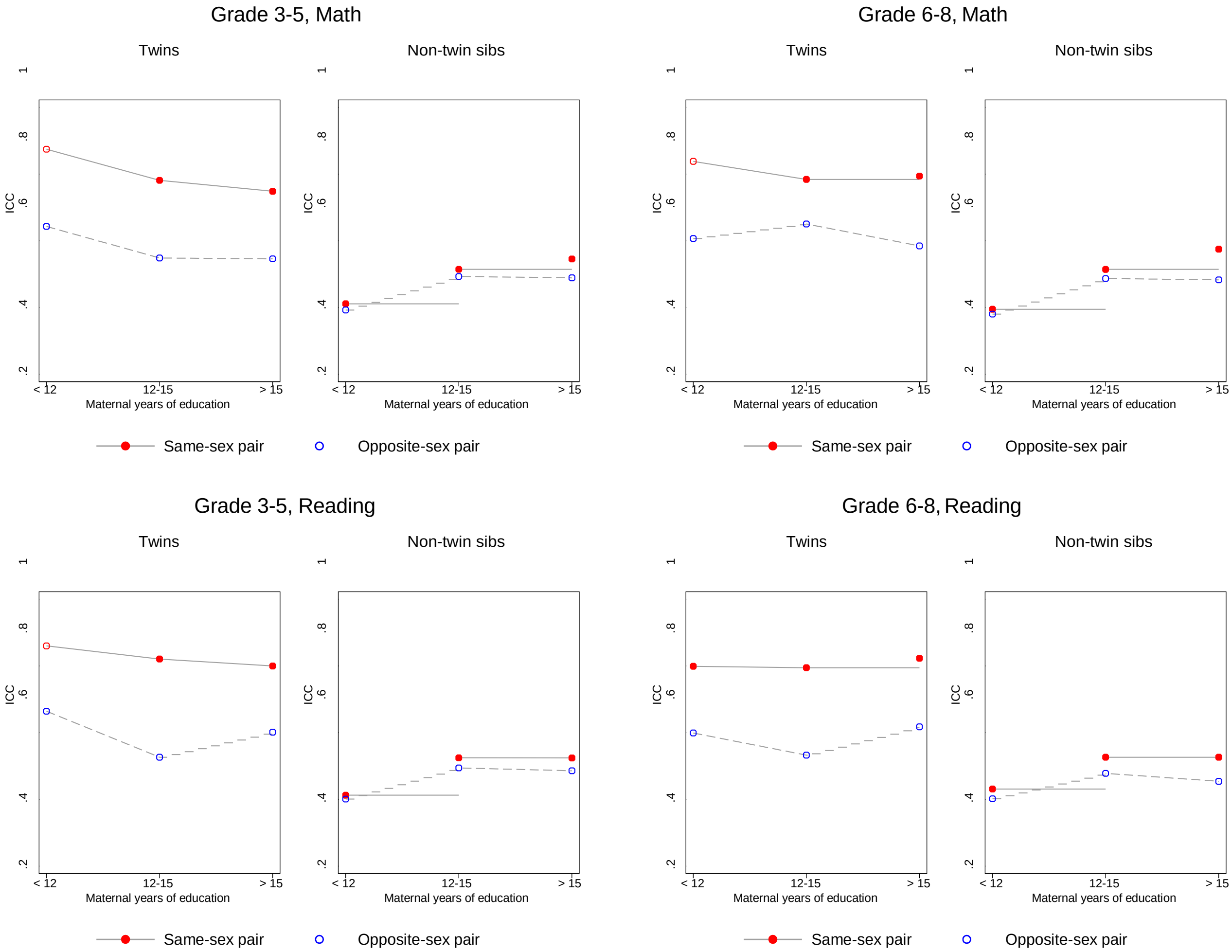
Note: The left-hand side figures present intraclass correlation coefficients among same-sex and opposite-sex pairs of twins and closely spaced siblings in grades 3 to 5 mathematics (top) and reading (bottom) FCAT test scores. The right-hand side figures present identical results for grades 6 to 8. Socioeconomic status is measured based on maternal years of education. Sample of white mothers. For estimation details see Figure 4.

Figure S16: Between- and within-pair variance in achievement test scores for same-sex and opposite-sex twins. Mothers up to age 30.



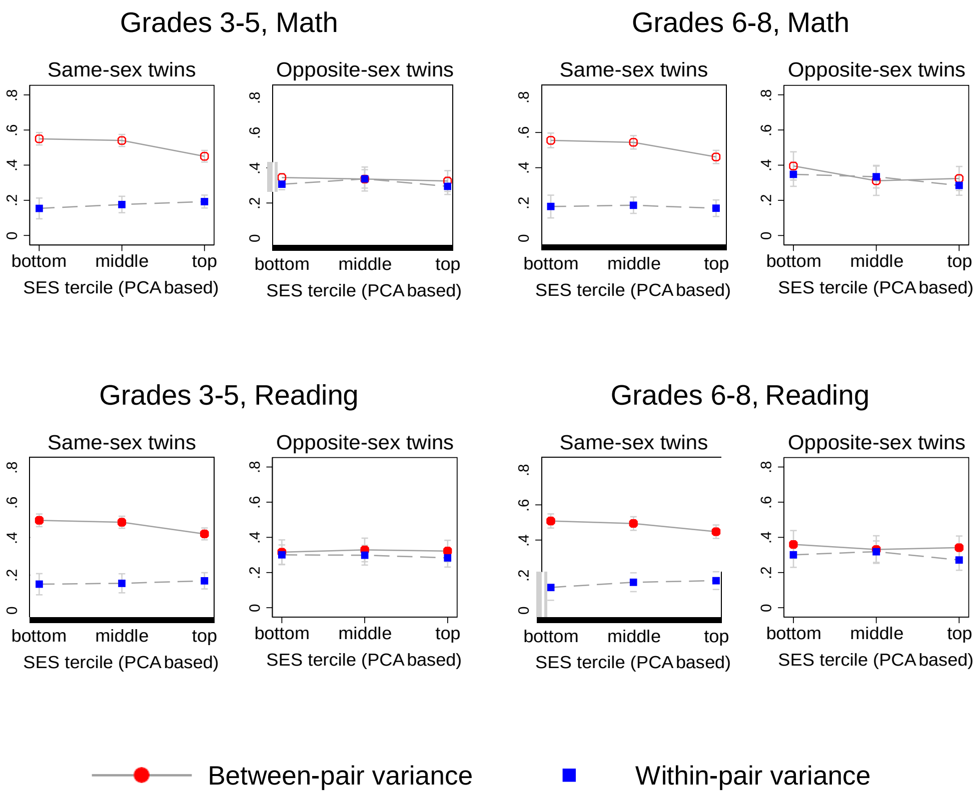
Note: The left-hand side figures present between- and within-pair variance among same-sex and opposite-sex twins in grades 3 to 5 mathematics (top) and reading (bottom) FCAT test scores. The right-hand side figures present identical results for grades 6 to 8. Socioeconomic status is measured based on maternal years of education. Sample of mothers up to the age of 30. For estimation details see Figure 3.

Figure S17: Intraclass correlation for same-sex and opposite-sex twin and non-twin sibling pairs. Mothers up to age 30.



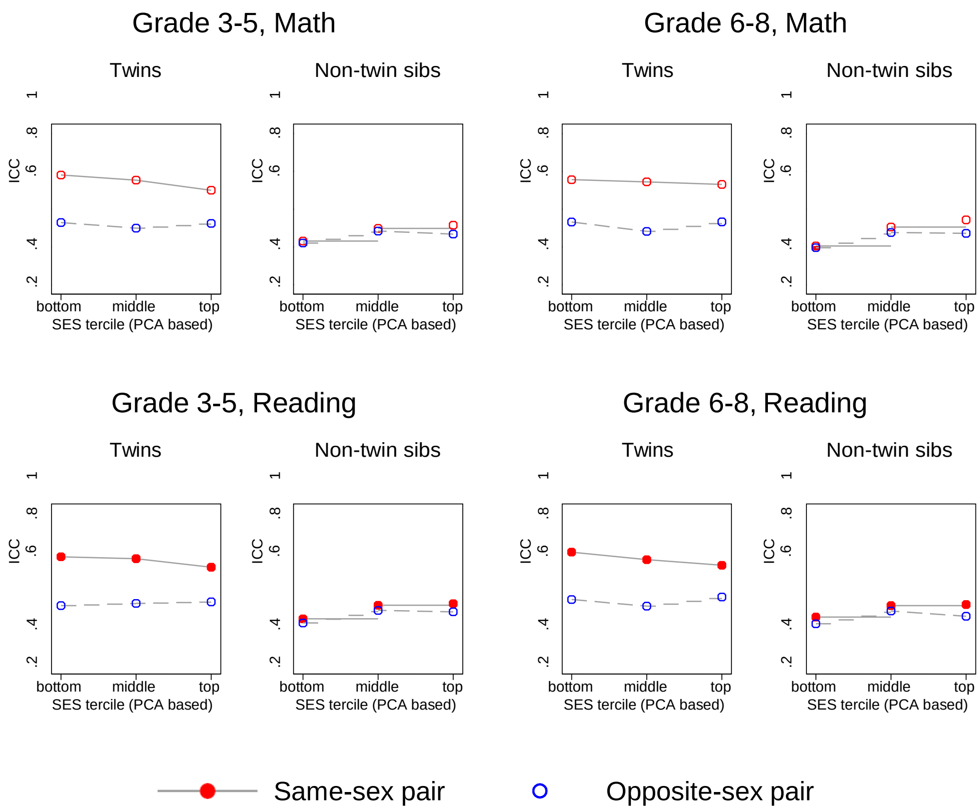
Note: The left-hand side figures present intraclass correlation coefficients among same-sex and opposite-sex pairs of twins and closely spaced siblings in grades 3 to 5 mathematics (top) and reading (bottom) FCAT test scores. The right-hand side figures present identical results for grades 6 to 8. Socioeconomic status is measured based on maternal years of education. Sample of mothers up to age of 30. For estimation details see Figure 4.

Figure S18: Between- and within-pair variance in achievement test scores for same-sex and opposite-sex twins. SES terciles based on PCA (excluding zip code income).



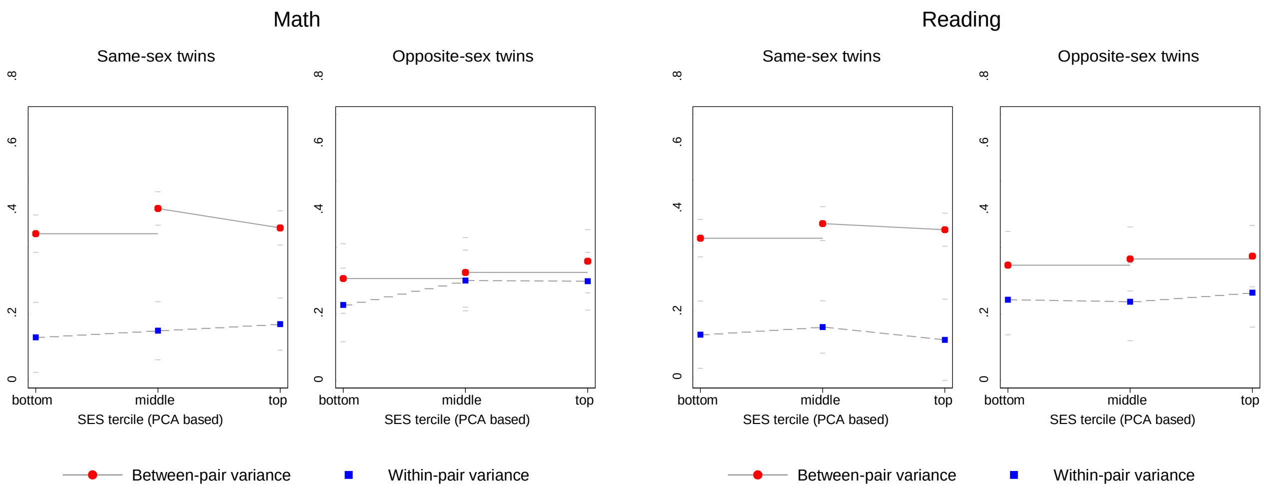
Note: The left-hand side figures present between- and within-pair variance among same-sex and opposite-sex twins in grades 3 to 5 mathematics (top) and reading (bottom) FCAT test scores. The right-hand side figures present identical results for grades 6 to 8. Socioeconomic status is measured based on index constructed using PCA where we include maternal years of education, medicaid paid birth, parents married, father present and father absent. For estimation details see Figure 3.

Figure S19: Intraclass correlation for same-sex and opposite-sex twin and non-twin sibling pairs. SES terciles based on PCA (excluding zip code income).



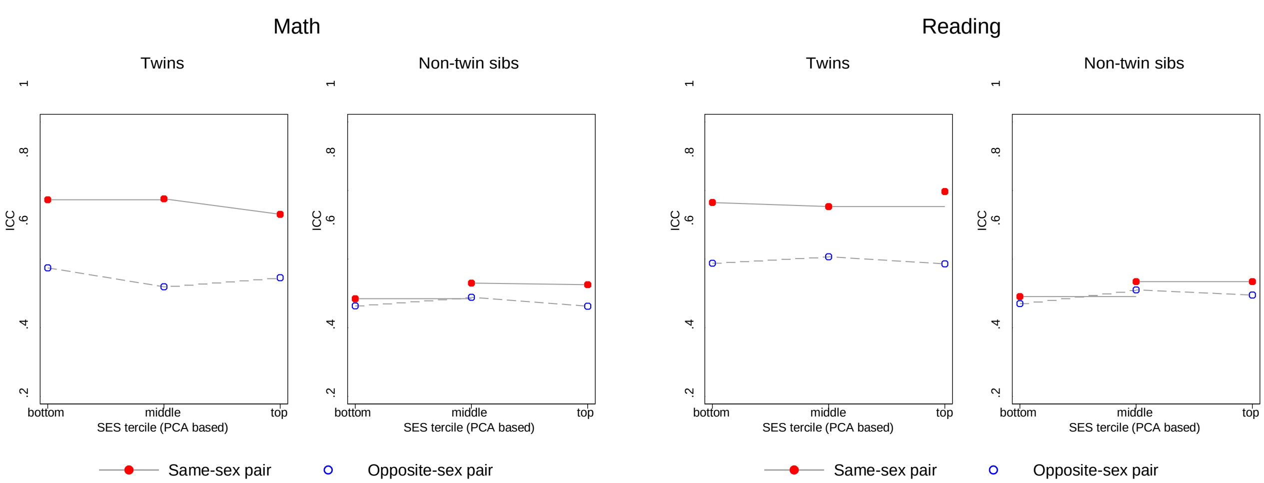
Note: The left-hand side figures present intraclass correlation coefficients among same-sex and opposite-sex pairs of twins and closely spaced siblings in grades 3 to 5 mathematics (top) and reading (bottom) FCAT test scores. The right-hand side figures present identical results for grades 6 to 8. Socioeconomic status is measured based on index constructed using PCA where we include maternal years of education, medicaid paid birth, parents married, father present and father absent. For estimation details see Figure 4.

Figure S20: Between- and within-pair variance in Stanford achievement test for same-sex and opposite sex twins. SES terciles based on PCA (excluding zip code income).



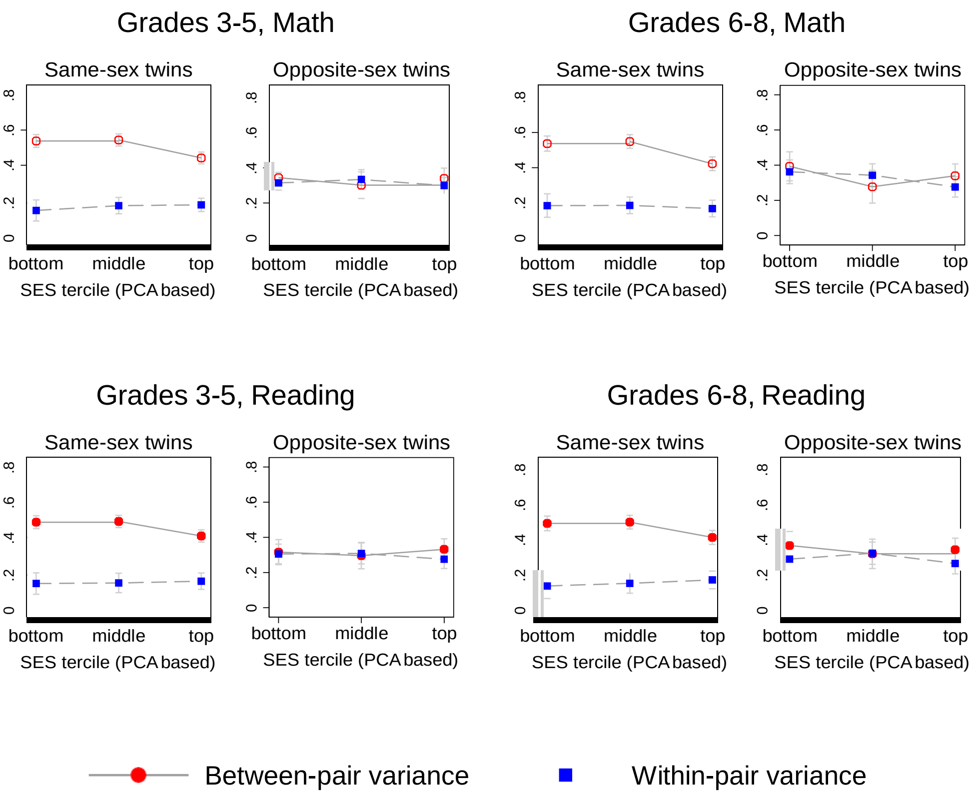
Notes: The left-hand side figures present between- and within-pair variance among same-sex and opposite-sex twins in grades 3 to 5 Stanford mathematics achievement test. The right-hand side figures present identical results for reading test. Socioeconomic status is measured based on index constructed using PCA where we include maternal years of education, medicaid paid birth, parents married, father present and father absent. For estimation details see Figure 3.

Figure S21: Intraclass correlations for same-sex and opposite-sex twin and non-twin sibling pairs on Stanford achievement test. SES terciles based on PCA (excluding zip code income).



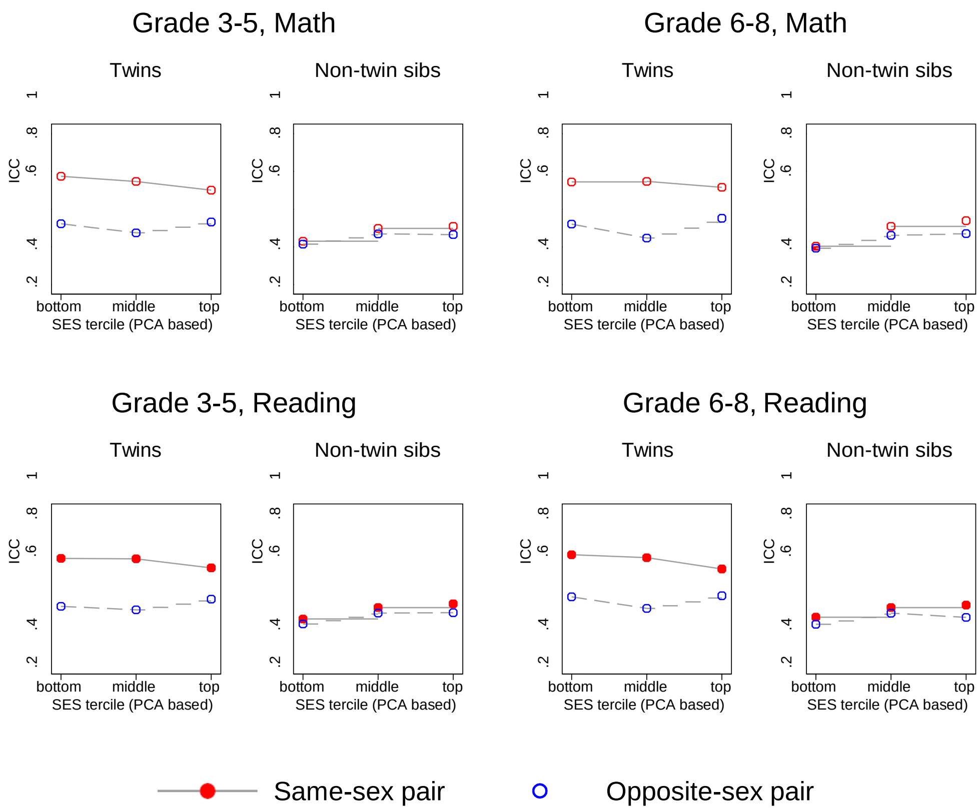
Note: The left-hand side figures present intraclass correlation coefficients among same-sex and opposite-sex pairs of twins and closely spaced siblings in grades 3 to 5 Stanford achievement test. The right-hand side figures present identical results for reading test. Socioeconomic status is measured based on index constructed using PCA where we include maternal years of education, medicaid paid birth, parents married, father present and father absent. For estimation details see Figure 4.

Figure S22: Between- and within-pair variance in achievement test scores for same-sex and opposite-sex twins. SES terciles based on PCA (including zip code income).



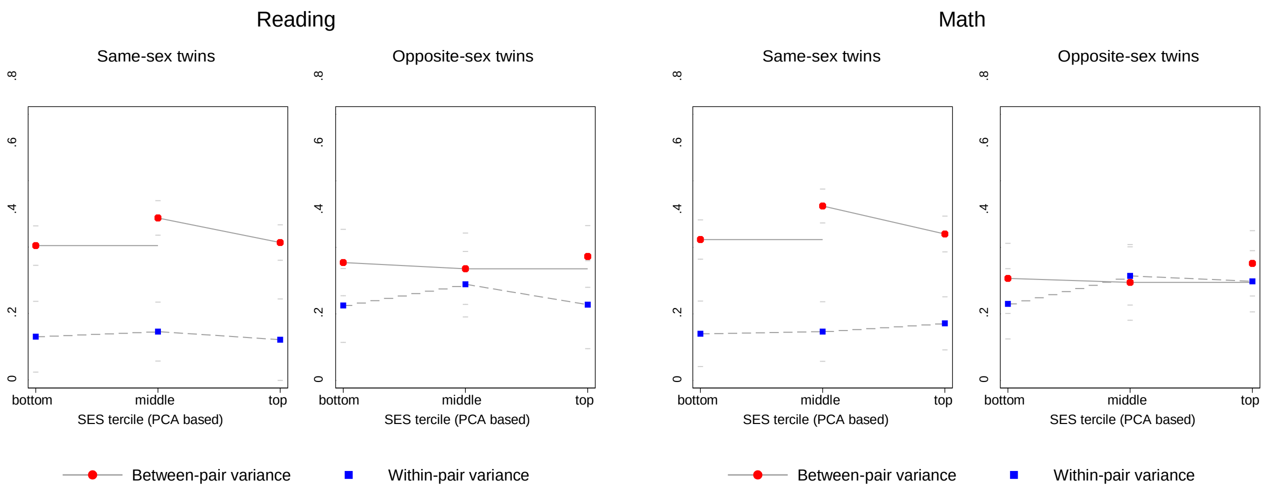
Note: The left-hand side figures present between- and within-pair variance among same-sex and opposite-sex twins in grades 3 to 5 mathematics (top) and reading (bottom) FCAT test scores. The right-hand side figures present identical results for grades 6 to 8. Socioeconomic status is measured based on index constructed using PCA where we include maternal years of education, medicaid paid birth, parents married, father present, father absent and median zip code income of residence at the time of child birth. For estimation details see Figure 3.

Figure S23: Intraclass correlation for same-sex and opposite-sex twin and non-twin sibling pairs. SES terciles based on PCA (including zip code income).



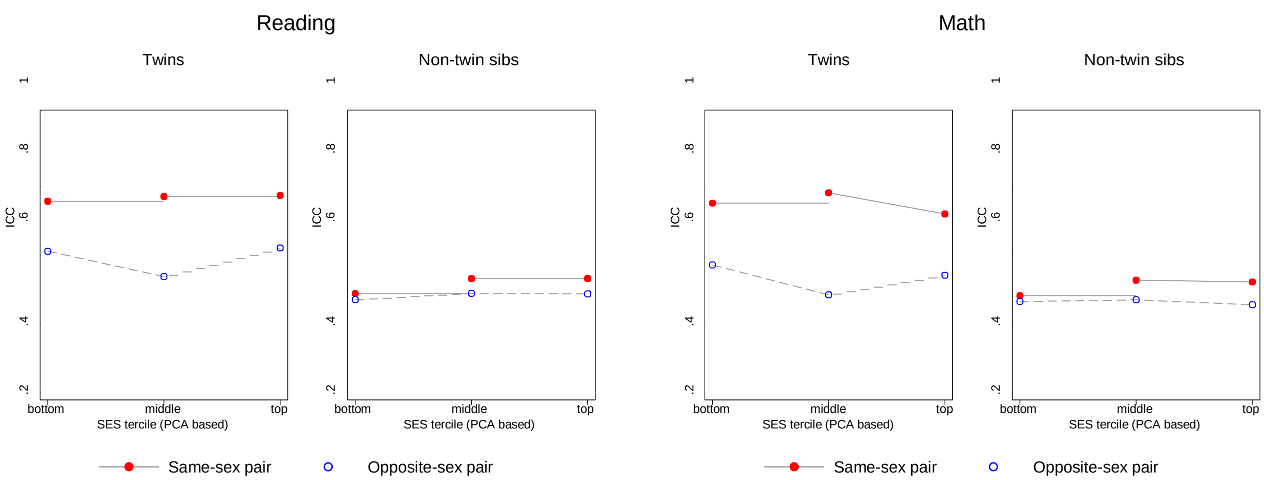
Note: The left-hand side figures present intraclass correlation coefficients among same-sex and opposite-sex pairs of twins and closely spaced siblings in grades 3 to 5 mathematics (top) and reading (bottom) FCAT test scores. The right-hand side figures present identical results for grades 6 to 8. Socioeconomic status is measured based on index constructed using PCA where we include maternal years of education, medicaid paid birth, parents married, father present, father absent and median zip code income of residence at the time of child birth. For estimation details see Figure 4.

Figure S24: Between- and within-pair variance in Stanford achievement test for same-sex and opposite sex twins. SES terciles based on PCA (including zip code income).



Notes: The left-hand side figures present between- and within-pair variance among same-sex and opposite-sex twins in grades 3 to 5 Stanford mathematics achievement test. The right-hand side figures present identical results for reading test. Socioeconomic status is measured based on index constructed using PCA where we include maternal years of education, medicaid paid birth, parents married, father present, father absent and median zip code income of residence at the time of child birth. For estimation details see Figure 3.

Figure S25: Intraclass correlations for same-sex and opposite-sex twin and non-twin sibling pairs on Stanford achievement test. SES terciles based on PCA (including zip code income).



Note: The left-hand side figures present intraclass correlation coefficients among same-sex and opposite-sex pairs of twins and closely spaced siblings in grades 3 to 5 Stanford achievement test. The right-hand side figures present identical results for reading test. Socioeconomic status is measured based on index constructed using PCA where we include maternal years of education, medicaid paid birth, parents married, father present, father absent and median zip code income of residence at the time of child birth. For estimation details see Figure 4.