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An Examination Of Gene X Socioeconomic Status Interactions For Reading Achievement

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AN EXAMINATION OF GENE X SOCIOECONOMIC STATUS INTERACTIONS FOR READING ACHIEVEMENT

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To dhh… without your love, support, and encouragement, this would not be possible.

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ABSTRACT

Reading is a critical skill that is influenced by socioeconomic factors. It is well-established that reading is influenced by genetic and environmental factors, and recent studies have suggested that genetic effects on reading may be moderated by socioeconomic factors. However, findings of such gene-environment interactions are inconsistent for reading and cognitive ability, and no known study has investigated moderating effects across the full range of reading ability in elementary-aged readers when foundational reading skills are established. The current study filled this gap in the literature by testing for moderating effects of six socioeconomic status (SES) variables on genetic and environmental influences on reading in a diverse sample of 1,709 twin pairs in third-fifth grades. Structural equation moderation models that allowed for a moderating effect of SES on the mean of reading as well as genetic and environmental variance components were fit separately for six SES variables. No significant genetic moderation was found, however, there was a pattern of moderation on shared environmental variance for four of the six SES variables. Overall, there was a trend of slightly more variance in reading in children of lower SES families and this increased variance was due to more variability in their shared environmental experiences.

INTRODUCTION

Over the last several decades literacy has become increasingly important in our technological society. Those with low literacy levels are more likely to live in poverty, receive public assistance, and less likely to be employed full-time (Kirsch, Jungeblut, Jenkins, & Kolstad, 1993; Kutner et al., 2007). In contrast, higher literacy levels are positively correlated with income levels, educational attainment, employment status, and community and civic involvement (Kutner et al., 2007). Furthermore, reading proficiently is critical to all aspects of education including completing high school and going on to postsecondary education. Lower educational attainment is associated with greater criminal behavior and incarceration, negative health outcomes, and drug and alcohol use (Crosnoe, 2006; Cutler & Lleras-Muney, 2006; Henry, 2010; Lochner, 2004). In sum, literacy and educational attainment are linked to nearly all aspects of quality of life and academic failure can have dramatic impacts on individuals and society as a whole (Lochner & Moretti, 2004).

Socioeconomic status (SES) is one factor related to both academic achievement and cognitive abilities (McLoyd, 1998; Noble, McCandliss, & Farah, 2007; White, 1982). Socioeconomic status ranks individuals (or families) hierarchically based on access to or control over resources such as wealth, power, knowledge, and status (Krieger, Williams, & Moss, 1997; Mueller & Parcel, 1981). As such, it can be indicator of parents' access to resources and therefore their ability to provide opportunities to their children.

There is much debate in the literature regarding what SES represents, whether it is a single construct, and how to best measure it (Bradley & Corwyn, 2002). However, the variables used most frequently to indicate socioeconomic status are education, occupation, and income (Smith & Graham, 1995). Educational attainment is among the most widely used indicators of socioeconomic status (Krieger et al., 1997; Sirin, 2005; White, 1982). Educational attainment is considered one of the most stable components of SES as it is typically established fairly early in life and generally does not change over time (Sirin, 2005). Beyond the obvious indication of knowledge that education represents, education level reflects access to both material and social resources as well as prestige in the social hierarchy (Krieger et al., 1997). In contrast to the relatively straightforward numeric values education and income provide, occupation scores must be constructed. Occupation scoring rubrics tend to be constructed of both the education and income typical for an occupation (e.g., Nam & Boyd, 2004), and some indices also include prestige and culture (e.g., Duncan, 1961). Thus, occupation reflects typical social and economic resources available to an individual of a given occupation. Occupation is more stable and therefore a better indicator of economic standing than income measured at a single time point (Hauser, 1994). Income is typically the most direct measure of material wealth available to researchers and is linked to potential social and economic resources. However, it is more volatile than other socioeconomic measures because it can vary dramatically based on short term conditions such as employment status and household composition (Hauser, 1994; Krieger et al., 1997). Additionally, it is frequently left unanswered by participants (Hauser, 1994; Krieger et al., 1997).

There seems to be some general agreement that these three indices or some combination thereof may be referred to as SES (Mueller & Parcel, 1981; Sirin, 2005). Each of the three indicators is used in research either alone or in various combinations to account for SES. Some empirical research has shown that all three indicators of SES are highly correlated among themselves and the outcome of interest (Bradley & Corwyn, 2002). In contrast, others have shown only moderate correlations among components of SES and have argued that each component is uniquely measuring an aspect of SES (Bradley & Corwyn, 2002; Sirin, 2005). Combinations of two or more are found to correlate more highly with academic achievement and cognitive outcomes (White, 1982). The best SES indicator may depend on the specific outcome variable of interest (Smith & Graham, 1995). In addition to education, occupation, and income, whether a student qualifies for free or reduced-price lunch (FRL) is frequently used in studies of academic achievement as an indicator of SES because it is based on a student's family income level (Sirin, 2005).

SES can also be measured at the aggregated level. A commonly used means of assessing SES at the aggregated level is via census data. Neighborhood SES is often characterized by census reports of income, receipt of public assistance, percentage of professionals in the neighborhood, percentage of residents with high school or college education, and joblessness (Leventhal & Brooks-Gunn, 2000). Aggregated SES measures characterize contexts beyond the home in which individuals develop. They are indicators of the social and economic well-being and resources in the community that are available to individuals.

The relationship between SES and academic achievement and cognitive abilities has been studied extensively over the last several decades and reviews of the literature have shown that correlations vary widely from near zero to very strong (r = .005 - .75; Sirin, 2005; White, 1982). This variability in the relationship between SES and academic achievement and cognitive ability is interesting in that it demonstrates that SES has a very strong relationship with cognitive skills under certain conditions and a very low relationship in others. Meta-analyses investigating the relationship between SES and academic achievement show that the magnitude of the effect is moderated by several factors including the type of SES measure, the type of academic achievement variable, and the age at which the measures were investigated (Sirin, 2005; White, 1982). White's (1982) meta-analysis shows that when the student is the unit of analysis, family income is mostly highly correlated with achievement (r = .32) followed by parental occupation (r = .20) and parental education (r = .19). Combinations of two or more SES components tends to raise the correlation with academic and cognitive outcomes (r = .23 - .33). Sirin's (2005) subsequent meta-analysis found similar effect sizes, but they were more consistent across type of SES measure (income r = .29, occupation r = .28, education r = .30), and also included free or reduced-price lunch (r = .33). Sirin (2005) compared the overall effect size obtained in his meta-analysis to a review of more than 300 meta-analyses (Lipsey & Wilson, 1993) and found that family level SES is one of the strongest correlates of academic performance. Though SES tends to be measured at the family level, aggregated measures of SES such as school or neighborhood SES are also used as predictors of achievement and cognitive abilities. Aggregated SES measures tend to result in higher correlations with achievement (Sirin, 2005; White, 1982).

Beyond environmental influences, it is well-established that both cognitive abilities and reading are influenced by genetic factors. In fact, for the most part, academic achievement and cognitive abilities have mostly shown substantial heritable influences and more modest environmental influences (e.g., Byrne et al., 2009; Dale, Harlaar, & Plomin, 2005; Gayan & Olson, 2003). However, heritability estimates are not uniformly high; some studies show more sizable influences of the environment (e.g., Taylor & Schatschneider, 2010). It is possible that heritability estimates vary because of the samples from which they were drawn. When genetic and shared environmental influences are reported, they reflect the mean levels of variability for the sample under investigation. When a more diverse sample with greater environmental variability is investigated, it is likely that shared environmental influences will be greater than in less diverse samples. One plausible explanation for greater shared environmental influences in more diverse samples is that there is simply greater shared environmental variance overall and thus the proportion of variance due to genetic influences is reduced. Alternatively, the proportion of variance due to genetic influences may vary due to specific differences in the environment (e.g., socioeconomic variables) that may moderate genetic influences on cognitive outcomes. Until recently G x E interactions were not tested in behavioral genetic models of cognitive and reading abilities so it is unknown whether reported heritabilities and environmental influences were truly constant across the range of environmental factors in extant studies or whether they simply reflect the mean of the samples while obscuring differences at the tails of the distribution.

Understanding whether such G x E interactions are operating has the potential to inform research and practice in a number of ways such as aiding in identifying particular environmental and genetic influences. A G x E interaction indicates that variation in the specific environmental moderator under investigation influences the genetic variability seen in a behavior to a greater or lesser degree across the range of that environment. To the degree that genetic influences account for a lesser proportion of the variability in a behavior, the environmental proportion of variance must be greater. If a greater proportion of the variability in cognitive outcomes for children at a particular level of the moderator is due more so to environmental rather than genetic factors then this offers opportunities to explore which environmental factors are having the greatest impact. For example, it would be informative to identify specific environmental factors for children with lower ability versus children with higher ability at the level of the moderator where the primary driver of observed differences is due to environmental influences. The current study contributes to such a possibility by establishing which levels of SES show the highest environmental influence. Additionally, if it is the case that particular environmental factors trigger genetic influences, it would be useful to identify such environmental triggers in order to prevent them (in the case of environmental factors that trigger deleterious genetic influences) or incorporate them into interventions (in the case of environmental factors that trigger positive genetic influences). Phenylketonuria (PKU) is well known example of a G x E interaction to illustrate the effects of environmental triggers given a genetic predisposition. Persons with a PKU genotype are not necessarily affected as a result of having the genotype; an individual must also have the environmental exposure to foods that contain phenylalanine in order to be negatively affected. Similarly, for cognitive outcomes a person may have the genotype putting them at risk to be learning disabled, but may never experience the environmental triggers to activate such deleterious genetic influences and therefore might present as a person with average ability. Conversely, it may be the case that a person has the genotype to be highly intelligent, but not have the environmental triggers or opportunities to realize this genetic potential. Finally, understanding whether gene X socioeconomic status interactions are at play is also useful in the search for specific genes in that searches can be more precisely targeted when the conditions under which the phenotype is expected are better understood.

Theories have been put forth postulating that such G x E interactions are in fact in play across the normal range of SES. Scarr (1992) proposed that environments will have little influence on genetic expression except in extremely negative environmental circumstances. She argues that in cases of “species-normal genes” that “species-normal social rearing environments” that fall within a normal range will be “functionally equivalent.” Environments that fall outside the normal range (e.g., more extreme environments such as deprivation) result in observable differences. She argues that outcomes are most related to genetic variation when environments are “good enough.” Thus, according to Scarr, it is only at the extremes of environmental disadvantage that genetic influences on cognitive outcomes should be lessened and not for middle- or upper-SES individuals. However, it is not clear at what point environmental disadvantage is extreme enough to reduce the genetic influences on behavior. Scarr (1992, p. 3) gives the example of “children trapped in crack houses of inner cities in the United States, locked in basements and attics by vengeful, crazy relatives,” but these are clearly severe cases of abuse and it is certainly plausible that lower heritability estimates could be seen at less extreme levels of disadvantage.

Bronfenbrenner and Ceci (1994) take some issue with Scarr’s viewpoint and instead propose that environments are the means by which proximal processes (i.e., “mechanisms of organism-environment interaction presumed to lead to particular kinds of developmental outcomes” p. 568-569) transform genotypes into phenotypes across the range on environments (not just at extreme disadvantage). More advantaged environments result in more proximal processes and thereby more genetic actualization, which is reflected in higher heritabilities. This is an interactive process of the environment and the genotype and to the extent that environments do not actualize genetic potentials, they are left unrealized. That is, it is not that those in more disadvantaged environments do not have the genetic potential, rather that they lack opportunities for proximal processes to realize the genetic potential. In sum, environmental influences will affect variability across the spectrum of environments, but there will be greater genetic influence on variability at the high end of the spectrum.

Historically, researchers have carried out studies to address the question of moderation of socioeconomic factors on the genetic influences of cognitive abilities, however, some early efforts had methodological flaws that drew criticism and called results into question (e.g., Allen, Pettigrew, Erlenmeyer-Kimling, Stern, & Scarr-Salapatek, 1973; Eaves & Jinks, 1972; Scarr-Salapatek, 1971). Other reports have been limited by insufficient sample size, study designs, and reporting that do not adequately address gene X socioeconomic interactions (e.g., Capron & Duyme, 1989; Fischbein, 1980; Nagoshi & Johnson, 2005). New advances in statistical techniques and larger available samples have led to subsequent investigations which have modeled G x E interactions.

Several recent studies have utilized regression-based approaches. One of the first such studies investigated moderation of genetic influences on reading and math achievement by socioeconomic factors in a large sample of children (*M* age = 9.58, *SD* = 3.08; van den Oord & Rowe, 1997). Socioeconomic indicators included family poverty status, highest grade completed by mother, highest grade completed by father, and employment level of father, each of which were analyzed independently. The authors reported only “general trends” that indicated simple linear changes in etiological variances that resulted in similar proportions of variance (i.e., heritabilities and shared and nonshared environmental influences) across levels of the moderators. Thus, though there was more overall variance in disadvantaged environments compared to advantaged environments, there was little evidence of G x E interactions.

Parental education was tested for moderation of genetic influences on verbal IQ in adolescents (*M* age = 16, *SD* = 1.7; Rowe, Jacobson, & van den Oord, 1999). Extended DeFries-Fulker (DF) regression analyses showed that heritability was moderated by level of parent education such that heritability was much higher (h^2 = .74) for those in well-educated families compared to those in less well-educated families (h^2 = .26). Guo and Stearns (2002) reanalyzed these data using mixed models and adding several SES indicators including the three traditional components of SES: mother’s education, mother’s occupation, and family income. All SES indicators were modeled as individual variables in the models rather than as a single SES composite variable. Findings were quite mixed in this reanalysis. Most of the SES variables investigated moderated etiological influences on verbal IQ such that heritability estimates were higher in more favorable conditions and lower in less favorable conditions. However, there was no moderation for maternal occupation and mother's education showed the opposite pattern of moderation reported for parental education by Rowe and colleagues (Rowe et al., 1999); heritability was higher for children of less educated mothers and lower for children of more educated mothers.

In studies of extremes of reading ability, parental education was found to moderate genetic influences on reading disability (Friend, DeFries, & Olson, 2008) and high reading ability (Friend et al., 2009) using DF analyses. For individuals (age = 8-20) in the reading disability study, group heritability (h_g^2 = .49) was slightly more influential than group shared environment (c_g^2 = .41) at low parental education levels. In contrast, for high levels of parental education, heritable influences were significantly greater (h_g^2 = .71) than shared environmental influences (c_g^2 = .22). The study of high reading ability children (age 6-12) showed a different pattern of moderation. Heritability was greater at lower levels of parental education and heritability was lower at higher levels of parental education. However, unlike these two studies of extremes of reading ability, a later study of reading did not find moderating effects. Reading across the range of ability as well as a subsample with reading disability in a similarly aged sample (age 10-20) found no moderating effects of parental education on genetic influences using DF analysis (Kirkpatrick, Legrand, Iacono, & McGue, 2011).

Though these regression approaches have attempted to test whether there are G x E interactions on cognitive outcomes, conclusions are limited by the statistical technique used. DF analyses seem to be better able to detect moderating effects than multilevel models and have detected interaction effects in three out of four studies, but whether these are truly G x E interaction effects is unknown. This is because DF regression analyses utilize transformed data and produce heritabilities directly. As a result, DF analyses obscure the etiological source(s) driving differential proportions of variance. That is, they fail to specify the etiological source of the change in variance that resulted in the proportional increase of heritable influences and decrease in shared environmental influences. There are several scenarios in which the magnitude of heritability increases and shared environmental influences decrease: 1) genetic variance increases while shared environmental variance decreases, 2) genetic variance remains stable while shared environmental variance decreases, or, 3) genetic variance increases while shared environmental variance remains stable. Thus, though there were reported G x E interactions in which magnitudes of heritability and shared environmental influences varied as a function of SES factors, it is unclear precisely which changes in etiological sources of variance led to the observed interaction. In such scenarios, SES factors are moderating heritability (i.e., driving changes in proportions of variance due to genetic influences), but not necessarily due to a G x E interaction.

In contrast, structural equation modeling (SEM) techniques allow for testing of moderation on specific etiological sources driving observed differences in heritabilities. Additionally, SEM allows for modeling of moderation on the means of the cognitive phenotype. This is important because phenotypic SES is related to cognitive outcomes and this correlation is likely due to both genetic and environmental sources. Attempting to model G x E interactions in the presence of genotype-environment correlations (r_{GE}) is likely to introduce bias. However, Purcell (2002) has shown that this bias diminishes when the main effects for the moderator are modeled. Since Purcell's (2002) introduction of the SEM model that directly tests moderation, several studies have used the technique.

In the initial study applying the technique to socioeconomic status and cognitive outcomes, SES was found to moderate the relationship between genetic influences and IQ in 7-year old twin pairs (Turkheimer, Haley, Waldron, D'Onofrio, & Gottesman, 2003). SES consisted of a combination of parental education, occupational status, and income. Structural equation models were fitted for FSIQ, VIQ, and PIQ separately. Significant G x E interactions were found for FSIQ and PIQ, but not VIQ which had an interaction in the same direction but that did not reach significance. Genetic influences on IQ were higher for children in higher SES families whereas they were negligible for children in lower SES families. Conversely, environmental influences (both shared and nonshared) were negligible at higher levels of SES but much higher at lower levels of SES.

After the finding of moderation for a younger sample, a subsequent study investigated whether such moderating effects were also at play later in life. Parental education was tested for moderating genetic effects on reading in an older adult sample (Kremen et al., 2005). Moderating effects were observed, however, these effects were observed on shared environmental influences but not genetic influences. This model resulted in higher heritability (h^2 = .69) and lower shared environmental influence (c^2 = .00) for those of more educated parents compared to those from less well-educated parents (h^2 = .21 and c^2 = .52). These proportions of change were driven not by a gene X parental education interaction, but rather a shared environmental X parental education interaction only.

In another replication effort, cognitive aptitude was investigated in 17-year old twin pairs taking the National Merit Scholarship Qualifying Test (Harden, Turkheimer, & Loehlin, 2007). Two socioeconomic status indicators, parental education and income, were investigated separately. Structural equation models showed that parental income moderated genetic influences on cognitive aptitude such that heritabilities were higher in more affluent families and lower in less affluent families. Despite demonstrating a similar pattern of results, the gene X parental education interaction didn't quite reach significance.

Socioeconomic status seemed to be moderating the etiological influences on cognitive outcomes as evidenced by three studies. However, the consistency and generalizability of these sorts of effects was questioned when no moderating effects were found in two subsequent studies. No moderation was observed in a sample of younger (*M* age = 26.56, *SD* = 3.76) and older (*M* age = 49.39, *SD* = 6.99) adults in which IQ scores were examined for moderation of socioeconomic variables on genetic influences (van der Sluis, Willemsen, de Geus, Boomsma, & Posthuma, 2008). Socioeconomic variables were analyzed separately and included parental education and mean real estate prices in participants' current residential neighborhood, a "crude estimate of income" (p. 357). Unlike previous reports, whole sample analyses showed no G x E interaction in this adult sample. The sample was further broken down into younger and older cohorts and males and females to test whether there was moderation for any of the four subgroups, and results showed no moderation of genetic influences and limited moderation of environmental influences for older males only. Older males from more highly educated families had greater shared environmental influences, and those in higher priced neighborhoods had greater nonshared environmental influences. The authors note that their sample sizes were small given the complexity of the analyses and a lack of observed moderation may have been due to insufficient power. Similarly, in a different study, parental education did not moderate genetic influences of cognitive ability in young adults (*M* age = 19.6, *SD* = 1.5; Grant et al., 2010).

Adding to the incertitude, mixed results were observed in a twin study investigating the moderating effects of neighborhood SES on prereading skills in kindergarten and reading in first grade (Taylor & Schatschneider, 2010). Median neighborhood income obtained from census data served as the neighborhood socioeconomic indicator and was trichotomized into low income (bottom 25%), middle income (26-74%), and high income (top 25%) groups. Multigroup structural equation models showed that genetic and shared environmental variances were equivalent across some income groups for some reading measures (suggesting no moderating effects), but significantly different across others (suggesting moderating effects). Two prereading skills showed no group differences, but one showed differential magnitudes of genetic influence such that heritabilities were higher for the low income than the high income group. There were group differences on both genetic and shared environmental influences for first grade reading which showed a greater impact of shared environmental than genetic influences for the low income group and the opposite pattern for the middle and high income groups.

In a study aimed at investigating when gene X socioeconomic environment interactions might emerge, Tucker-Drob and colleagues looked at twins measured at 10 months and then again at 2 years of age on mental ability (Tucker-Drob, Rhemtulla, Harden, Turkheimer, & Fask, 2011). Structural equation models tested for moderation effects of a composite measure of SES. No moderation was detected at 10 months, however, SES showed moderating effects on both genetic and shared environmental influences on mental ability at 2 years old such that shared environmental influences were greater at low levels of SES and heritability was greater at high levels of SES. These same twins were followed up at age 4 when they were tested on prereading skills and early math skills (Rhemtulla & Tucker-Drob, 2012). SES significantly moderated genetic effects on early math skills, but no moderation was found for prereading skills.

Most recently, the moderating effects of SES on IQ were investigated in a large twin sample longitudinally from ages 2-14 (Hanscombe et al., 2012). Interaction effects were tested separately for eight time points and though the results across ages were somewhat mixed, the most consistent pattern that emerged was one of no gene X SES interaction. Families of lower SES tended to have more overall variance and this increase was due to a shared environment X SES interaction.

Overall, the literature is mixed with regard to finding moderating effects of SES on genetic influences for cognitive outcomes. Half of the studies that used regression based approaches showed moderating effects though it is unclear whether these effects were driven by genetic or environmental sources of variance. Of the eight studies that have tested for moderating effects directly using moderation SEM, six have found at least some moderation, but two have not. In many of the studies finding moderation, moderation was not always found on all variables investigated. Further, observed moderating effects were not always on genetic influences; some were on shared environmental effects only. Of those finding moderation, patterns of results mostly supported the bioecological framework.

Given the mixed results, additional studies are necessary to understand whether socioeconomic status moderates the etiological influences on cognitive outcomes. Ideally, a study testing for such moderating effects will have a twin sample that is representative of the full range of SES and test moderation directly using SEM. Twin studies are particularly advantageous in behavioral genetic studies because they provide both genetic and environmental comparability. Monozygotic (MZ) twins share all of their genotype, whereas, dizygotic (DZ) twins and full-siblings share approximately half of their genotype. Unlike other siblings, both MZ and DZ twins experience the same shared environmental factors at the same time in development. Comparison of studies that include non-twin siblings versus twin studies show that phenotypic correlations are lower for non-twin siblings than DZ twins on cognitive outcomes, and this seems to be a result of twins sharing more cognitive-relevant experiences because they are exactly the same age (Koeppen-Schomerus, Spinath, & Plomin, 2003). Thus, twin studies are better equipped to detect effects that may result from particular environmental encounters. The use of non-twins may explain some of the discrepant findings of moderation on cognitive outcomes. Extant studies reviewed that included relatives beyond twins were less likely to detect moderating effects, but only one study that was limited to twins failed to find moderating effects (Grant et al., 2010). It is also important that the full range of SES be represented in the twin sample because if a G x E interaction operates across the full range of SES, to the extent that the range of SES represented in a sample is restricted, the likelihood of detecting such an interaction is likely to attenuate.

To date, no known study has investigated moderating effects of SES using moderation SEM across the full range of reading ability in elementary-aged readers when foundational reading skills are being established. Only one study has tested for a G x E interaction on reading using a moderation SEM and the sample was older (41 – 58 years old; Kremen et al., 2005). The current study filled this gap in the literature by investigating whether socioeconomic status moderated the genetic and environmental influences on reading comprehension in elementary school using a diverse twin sample. Several SES variables were available and each was tested separately in order to determine if there were differential moderation effects based on particular aspects of SES. Based on the reviewed literature, it was hypothesized that moderation effects would be found and that they would be consistent with the bioecological model.

METHOD

Participants

Twins in the current report were part of the Florida Twin Project on Reading (FTP-R), a longitudinal study of reading. At the time of this report, the FTP-R included approximately 2,500 twin pairs. Potential twins were identified and recruited from Florida's Progress Monitoring and Reporting Network (PMRN) through a combination of direct mailings to parents and/or mailings sent to school to be carried home by a randomly selected member of the twin pair. Recruitment packets contained a letter explaining the project and a zygosity questionnaire composed of five questions that have shown to be predictive of zygosity with over 95% accuracy (Lykken, Bouchard, McGue, & Tellegen, 1990). The PMRN is a database containing both longitudinal progress monitoring and achievement data for reading on nearly two million students attending schools in both rural and urban areas throughout the state in grades kindergarten through twelve.

In addition to the reading measures available in the PMRN, qualification for free or reduced-price lunch (FRL), a socioeconomic indicator, is also available. An additional socioeconomic indicator for twins' families is the average of median incomes reported in U.S. census data for the neighborhoods of twins. More direct socioeconomic measures were collected on a subset of twin families that participated in a behavior and environment study in 2010. All these data were collected via mailed questionnaires. Mother's and father's education, parental occupation, and family income data were collected from twins' parent or legal guardian with whom they live as part of a questionnaire that contained demographic, environmental, and behavior questions. All same-sex twin families in the FTP-R (*N* = 1,624) were recruited to participate and completed questionnaires were received from approximately 43% of families. The large majority (94.92%) were completed by the biological mother (87.37%) or biological father (7.55%).

Due to the longitudinal nature and data collection procedures of the FTP-R, data were not available for all twins on all measures. The current study examined reading comprehension and socioeconomic status in grades 3, 4, and 5, and, therefore, only included twins from these grades for whom reading comprehension and socioeconomic data were available. When reading comprehension scores were not available for both twins in grade three, scores were used from grade four or five, as possible. A twin pair was included in the study if at least one twin in a twin pair had a reading comprehension score. Reading data were collected over the 2005-2006 through 2010-2011 school years. Only data for twins who completed the same grade during the time which the assessment was administered were used. Free or reduced-price lunch and census SES data were available for the majority of twin families in the FTP-R, but SES variables collected as part of the questionnaire study are available for a more limited subsample of the FTP-R. Table 1 provides descriptive statistics on reading comprehension and the SES variables for twins with data available for analyses versus those with missing data. Overall, missing data is associated with slightly more disadvantage on the other variables.

A total of 1,709 twin pairs had available data for the current study. For the purposes of this paper, two smaller subsets of data were created. The first is the FRL/census sample which includes all twins with reading data and FRL or census data and consisted of 583 MZ pairs (296 female; 287 male) and 1,122 DZ pairs (283 female; 274 male; 565 opposite-sex). Reading comprehension data were mostly collected when twins were in third grade (*M* grade = 3.29, *SD* = .57; *M* age = 9.56, *SD* = .78). Parents could report race/ethnicity based on categories offered by the state of Florida, and by parent-report, the composition of the sample was: 0.12% American Indian, 1.47% Asian, 16.54% Black, 24.11% Hispanic, 4.28% Mixed, and 52.26% White (data for the remaining 1.23% were unavailable). Means and standard deviations for all available SES variables are presented in Table 1. This sample is relatively representative of the state of Florida with regard to two SES variables for which data are also available at the state level, receipt of FRL and census median income. FRL status reported in this study reflects the twins' FRL at the time reading data were collected and during this time FRL eligibility ranged from 45.39% - 56.01% for the state of Florida (FDOE, 2011). The reported 2000 census median income for all households in Florida was $38,819 (U.S. Census Bureau, 2002), which is just less than the mean neighborhood median incomes in the current sample.

The second sample consists of all twins with reading data and SES data (parental education, parental occupation, and family income) from the behavior and environment questionnaire and will be referred to as the Questionnaire sample. This sample included 237 MZ pairs (126 female; 111 male) and 232 DZ pairs (123 female; 109 male), and nearly all (*N* = 466) of these twin pairs were also included in the FRL/census sample. Reading comprehension data were mostly collected when twins were in third grade (*M* grade = 3.29, *SD* = .77; *M* age = 9.55, *SD* = .77). The composition of this sample was: 0.43% American Indian, 1.71% Asian, 10.87% Black, 21.11% Hispanic, 5.12% Mixed, and 59.70% White (data for the remaining 1.07% were unavailable). Means and standard deviations for all available SES variables show that the twin families who completed the questionnaire are somewhat more advantaged than non-responders (see Table 1).

Measures

Florida Comprehensive Assessment Test Sunshine State Standards (FCAT). The FCAT is a group administered, criterion-referenced test administered to all students at the end of third through fifth grades throughout the state of Florida that assesses the extent to which students have achieved mastery of "Sunshine State Standards." FCAT Reading tests four clusters of skills: words and phrases in context; main idea, plot, and purpose; comparisons and cause/effect; and reference and research. The reading portion of the FCAT consists of 6 to 8 informational and literary reading passages followed by 6 to 11 multiple choice items for each passage (FDOE, 2005).

FCAT has been shown to be a reliable and valid measure with reliability ranges from .85 to .90 for the reading section. Further, a series of expert panel reviews and data analyses have established test score content and concurrent validity (FDOE, 2007). Additionally, the construct validity of the FCAT as a comprehensive assessment of reading outcomes has received strong support in an empirical analysis of its relationships with a variety of other reading comprehension, language, and basic reading measures (Schatschneider et al., 2004). FCAT is reported using a scale score ranging from 100–500 (FDOE, 2005).

Free or reduced-price lunch status. Free or reduced-price lunch status (FRL) was reported by twins' schools through the PMRN. A student is eligible for free lunch if their family's income is at or below 130% of the poverty level (USDA, 2010). Students whose family income is between 130% and 185% of the poverty level qualify for reduced-price lunch. For the 2010-2011 school year, the most recent school year in the current study, a family of four had to have an annual income of less than $28,665 to qualify for free lunch and $40,793 to qualify for reduced-price lunch according to U.S. government guidelines (USDA, 2010). Students were classified as either receiving FRL or not.

Neighborhood Income. The most recently available data from the U.S. Census Bureau (1999) on median family income for neighborhood by ZIP code was used as a socioeconomic indicator of the of the twins’ neighborhood. Census median family income data were matched to the ZIP code of the twins’ reported address.

Parental Education. Parents were asked to report the highest level of education completed separately for the biological mother and biological father. Parental education was assessed using a multiple choice format on a scale of 1 (“Grade 6 or less”) to 8 (“Completed graduate or professional school”; see Appendix C). For the context of this study, parental education was investigated as an environmental SES indicator. As such, when twins’ primary caregiver was not one or both of their biological parents, the biological parents' reported education level was not considered as the parental education environmental SES variable. Parental education was the mean of parents' reported education levels when data were available for both parents, or the education level of one parent if only one was available.

Parental Occupation. The occupation of the parent completing the questionnaire was assessed using the open-ended question, “What is your occupation?” Occupation was subsequently coded using the Barratt Simplified Measure of Social Status (Barratt, 2006) occupational codes which are updated from the widely used Hollingshead Four Factor Model (Hollingshead 1975).

Household Income. Parents reported the current household income on a 6-point scale where 1 was “less than $10,000” and 6 was “$90,000 or more” (see Appendix C).

Barratt/Hollingshead SES. The Hollingshead Four Factor Model (Hollingshead 1975) incorporates education and occupation ranked on ordinal scales for an individual or both members of a couple, as applicable. The Hollingshead education score ranges from “1- Less than seventh grade” to “7- Graduate professional training (graduate degree)”. Education was measured on a slightly different scale in the current study and these categories were scored as the most comparable Hollingshead category (see Appendix C). The Hollingshead occupation score ranges from “1- Farm Laborers/Menial Service Workers” to “9- Higher Executives, Proprietors of Large Businesses, and Major Professionals”. Barratt Simplified Measure of Social Status (Barratt, 2006) occupational codes which are updated from Hollingshead were used. The education score is weighted by a factor of three and occupation is weighted by five. The family level Barratt/Hollingshead SES score is the sum of weighted education and occupation for individuals, or the average of these scores for couples.

Analytic Plan

Analyses began by evaluating the basic assumptions of the twin method. Descriptive statistics were calculated separately for the FRL/census and Questionnaire samples in order to test for mean and variance differences across zygosity. Prior to conducting twin analyses, reading scores were corrected for potential effects of age and sex (McGue & Bouchard, 1984). Phenotypic correlations between reading and each of the SES variables were computed to assess the relationship between reading and SES as well as the degree of overlap among the SES variables. Twin correlations for MZ and DZ twins were calculated for each of the SES variables. Descriptive statistics and twin correlations were also calculated for MZ and DZ twins for levels of the SES variables in order to examine the trends in mean and variance differences across levels of these moderators.

Structural equation model fitting with full-information maximum-likelihood was used to test for moderating effects of SES on genetic variance (A; inherited additive genetic influences), shared environmental variance (C; environmental influences that cause siblings to be more similar), and nonshared environmental variance (E; environmental influences unique to the individual sibling as well as error) directly (see Figure 1) using the following biometrical model:

$$\mathrm{Var}\,(P) = (a + \beta_X M)^2 + (c + \beta_Y M)^2 + (e + \beta_Z M)^2$$

Where P is the reading phenotype, M is the value of the moderator (socioeconomic indicator), β_X quantifies genetic moderation, β_Y quantifies common environmental moderation, and β_Z quantifies nonshared environmental moderation. Moderator effects on the means (denoted as β_M in Figure 1) are also included in order to allow for main effects on the outcome variable (reading), and to control for potential r_{GE} (Purcell, 2002). Thus, the residual variance is decomposed into genetic influences (A), shared environmental influences (C), and nonshared environmental influences (E). The significance of β_X, β_Y, and β_Z indicate moderation of genetic, shared environmental, and nonshared environmental influences, respectively. Significance of the moderation parameters is evaluated by 95% confidence intervals for each parameter as well as evaluation of model fit statistics.

The expected covariances are:

$$\mathrm{Cov}(P_1,P_2)_{MZ} = (a + \beta_X M)^2 + (c + \beta_Y M)^2$$

$$\mathrm{Cov}(P_1,P_2)_{DZ} = 0.5*(a + \beta_X M)^2 + (c + \beta_Y M)^2$$

These covariances are also reflected in Figure 1. MZ twin pairs share 100% of their genotype and DZ twin pairs share approximately 50% of their genotype (on average), so correlations between twin pairs are fixed to 1 and 0.5, respectively. By definition, shared environment for both MZ and DZ are the same, so correlations are fixed to 1.

A series of models were fit to all available data using the Mx structural equation modeling program (Neale et al., 2006). The Mx program handles missing outcome variables (i.e., reading) using full-information maximum likelihood, but is unable to handle missing covariates (i.e., SES) and drops cases with missing covariate data. The saturated and nested models were compared to determine significance. Comparison of the fit of competing nested models used the Likelihood-Ratio Test which is the difference in chi-square distributed fit functions (-2LL). Akaike's Information Criterion (AIC; Akaike, 1987), an index of goodness-of-fit and parsimony, was used as the indicator of the best-fitting model. Lower AIC indicates a better balance of goodness-of-fit and parsimony and, therefore, a preferred model. Simulation studies have shown that the lowest AIC criterion selects the correct interaction model in the majority of cases (Purcell, 2002).

The best-fitting model was identified by successively dropping parameters as outlined by Purcell (2002). Specifically, the following models were fit for each SES variable separately:

1) Full moderation model. The fully moderated model allows moderation on all parameters. That is, genetic (A) and environmental (C and E) influences and means are allowed to vary across levels of the moderator. This saturated model served as the base model to which all other models were compared.

2) No moderation model. The standard ACE model assumes stability across levels of the moderator in means, overall phenotypic variance, and genetic and environmental influences on variances. This restricted model was compared to the full moderation model. If the difference in fit by the addition of the four moderation parameters (β_M, β_X, β_Y, and β_Z) was not significant, then the moderator was likely not adding much additional information. However, if the addition of the four parameters was significant, then the moderator likely did have an effect on one or more parameters.

3) Moderation models. If the comparison of the full moderation model to the no moderation model showed that dropping the moderation parameters resulted in a significant decrement of fit, then seven additional models that included all possible combinations of moderation effects were

fit. Each of these models was compared to the full moderation model and model fit statistics were evaluated in order to determine the source of moderation effects. The moderated means model only includes the β_M interaction parameter which allows mean levels of reading to vary across levels of the moderator, but assumes stability across levels of the moderator in overall phenotypic variance, and genetic and environmental influences on variances. Moderation on the means (β_M) was also included in all models that included moderation on variances (i.e., β_X, β_Y, and β_Z) to prevent potential r_{GE} bias in estimation of these interactions (Purcell, 2002). Thus, the significance of the interactions between the moderator and additive genetic effects (β_X), shared environmental effects (β_Y), and nonshared environmental effects (β_Z) was tested by comparing the full moderation model in which these were fit with nested models in which they were dropped (i.e., set to zero). The best-fitting model was the model with the lowest AIC, that is, the model that showed the best fit relative to parsimony.

RESULTS

Means and standard deviations for reading are presented by zygosity in Table 2. An assumption of the twin method is that both MZ and DZ twins are exposed to equal environments and therefore should have approximately equal means and variances. There were mean differences in reading by zygosity in the FRL/census sample ($t_{(3334)} = 4.276$, $p < .001$), though the comparison likely only reached statistical significance given the large sample size as the effect size was small ($d = .16$). There were no mean differences by zygosity for the Questionnaire sample ($t_{(924)} = 1.254$, $p = .210$). There were no significant variance differences for reading by zygosity for either the FRL/census sample (Levene's $F = 0.295$, $p = .587$) or the Questionnaire sample (Levene's $F = 1.271$, $p = .260$). All reading scores were corrected for age and sex prior to conducting twin analyses to control for potential age and sex effects (McGue & Bouchard, 1984).

Phenotypic correlations between reading and SES variables are presented in Table 3. Reading tended to have a modest correlation with the SES variables. The correlations between the SES variables had a greater range indicating some overlap in the aspects of SES captured in the measures, but also some specificity. Intraclass correlations for twins are presented separately for MZ and DZ twins for each SES variable in Table 4. Approximate standardized (i.e., proportional) estimates of genetic, shared environmental, and nonshared environmental estimates can be derived from these correlations. Doubling the difference of correlations between MZ and DZ twins results in an estimate of genetic influences. A shared environmental estimate is calculated by doubling the DZ correlation and then subtracting the MZ correlation. Nonshared environment is estimated by subtracting the MZ correlation from one. Inspection of the twin correlations suggested that additive genetic and shared environmental factors were likely significant sources of variance. Thus, an ACE model was selected for the moderation models. Additionally, a pattern of higher shared environment and lower genetic influences for those at lower levels of the SES moderators and lower shared environment and higher genetic influences for those at higher levels of the SES moderators suggested moderation. An additional rough estimate of potential moderation is inspection of variances across levels of the SES moderators. The standard deviations in Table 2 showed a pattern of somewhat more variance at lower levels of SES. Though this rough estimate of variances across levels of the moderators used illustrative groups based on standard deviations, it is important to note that the formal moderation analyses tested for moderation using the continuous SES moderators. The observed pattern of variances also serves as a check that the moderation SEM variances are accurately capturing the data. Indeed, this is the case; the pattern of increasing variance at lower levels of the SES moderators in the observed variances can be seen in the full moderation and best-fitting moderation models in Figure 2.

Results for moderation analyses of reading by each of the SES variables are presented separately below. For each of the SES variables, graphical summaries of the standard ACE model, full moderation model, and best-fitting model are presented in Figure 2. The standard ACE model that does not consider moderation effects is the model that is typically reported in studies and serves as a comparison to the moderation models. The full moderation model which models all moderation parameters (i.e., genetic, shared environmental, nonshared environmental, and means) generally captures interaction parameters well and serves as a guide to the best-fitting model (Purcell, 2002). The best-fitting model was chosen as the model with the lowest AIC as described above. Additionally, the parameter estimates for these three models are presented in Table 5 for each of the SES variables. Whether observed interaction effects are due to sampling error can be evaluated by whether confidence intervals for moderation parameters are bounded by zero and through comparison of model fit statistics between nested models that include the parameters and those in which they are dropped (i.e., set to zero). All model fit statistics are presented in Table 6.

Free or Reduced-Price Lunch

The full moderation model for FRL in Figure 2 shows a slight increase in genetic variance and a slight decrease in shared environmental variance across the levels of FRL. The no moderation model (Model 2) could not be accepted over the full moderation model (Model 1; Table 6) indicating some significant moderation. Neither the genetic nor shared environment interaction parameters reached significance as can be seen by the inclusion of zero in the 95% CIs in Table 5. Similarly, the change in -2LL showed only a marginally significant decrement in fit when moderation on A was dropped from the model (Model 4) and when moderation on C was dropped from the model (Model 5; Table 6). The only interaction parameter that reached significance was for the means indicating that reading scores were lower for those receiving

FRL. The best-fitting model was the model that included moderation on the means (Model 3, Table 6) and is shown in Figure 2.

Neighborhood Income

The full moderation model for Neighborhood Income shown in Figure 2 is very similar to that of FRL with a slight increase in genetic variance and a slight decrease in shared environmental variance across the levels of the moderator. Additionally, Neighborhood Income shows a slight decrease in nonshared environmental variance. The no moderation model (Model 2) could not be accepted over the full moderation model (Model 1; Table 6) indicating some significant moderation. Also similar to FRL, the only interaction parameter in the full moderation model that was not bounded by zero was the means interaction parameter (Table 5) indicating that as Neighborhood Income increased so did reading scores. The nonshared environmental interaction parameter approached significance in the full moderation model (Table 5), and when moderation on E was dropped from the model (Model 6) there was a marginal decrement in fit (Table 6). Though these indicators did not reach significance, the model that included moderation on E (Model 9) had the lowest AIC (Table 6) and is presented as the best-fitting model in Figure 2. It should be noted that the model that included moderation only on the means (Model 3) had only a slightly higher AIC, but nonetheless provided a slightly worse fit to the data.

Parental Education

The full moderation model for Parental Education presented in Figure 2 shows a decrease in both genetic and shared environmental variance across levels of the moderator. Again, the no moderation model (Model 2) could not be accepted over the full moderation model (Model 1; Table 6) indicating some moderation. As Table 5 shows, the only interaction parameter that reached significance was the means interaction parameter. Similarly, no models that dropped A, C, or E moderation parameters showed a significant decrement in model fit (Table 6). However, the model with the lowest AIC was the model that included moderation on both the means and C. Though the significance of the shared environment interaction parameter in the best-fitting model shows an increase over its significance in the full moderation model (Table 5), it does not quite reach significance.

Parental Occupation

The full moderation model in Figure 2 shows a more substantial decrease in shared environmental variance, an increase in genetic variance, and a slight decrease in nonshared environmental variance across level of Parental Occupation. The no moderation model (Model 2) could not be accepted over the full moderation model (Model 1; Table 6) indicating some significant moderation. Table 5 shows that the interaction parameters for means and the shared environment terms reached significance, and that the interaction terms for genetic and nonshared environment terms approached, but did not reach, significance. Similarly, inspection of model comparisons in Table 6 shows a significant decrement in fit for all models in which moderation on C was dropped (Models 5, 7, and 9), but only a marginally significant decrement in fit when moderation on A (Model 4) and E (Model 6) were dropped. Though the full moderation model (Model 1) and the model that includes moderation on the means and C (Model 8) had very similar AICs, the AIC for the full moderation was lower and was therefore selected as the best-fitting model.

Household Income

The full moderation model for Household Income in Figure 2 shows a very slight increase in genetic variance and a decrease in both shared and nonshared environmental variance. As above, the no moderation model (Model 2) could not be accepted over the full moderation model (Model 1; Table 6) indicating some significant moderation. Parameter estimates and 95% CIs in Table 5 show that interaction parameters for the means and nonshared environment are significant, but genetic and shared environment interaction parameters are not. All models in which moderation on E was dropped (Models 6, 7 and 8) showed a significant decrement in fit. The AICs were quite close for the model that included moderation on the means and E (Model 9) and the model that included moderation on means and both C and E (Model 4). Model 4 had the lower AIC and was therefore selected as the best-fitting model. Parameter estimates in Table 5 for the best-fitting model show a significant nonshared interaction, but a shared environment interaction that approaches, but does not reach, significance.

Barratt/Hollingshead SES

The full moderation model in Figure 2 for Barratt/Hollingshead SES shows a very similar pattern as Parental Occupation with a fairly substantial decrease in shared environmental variance, an increase in genetic variance, and a slight decrease in nonshared environmental variance. As with the other SES variables, the no moderation model (Model 2) could not be accepted over the full moderation model (Model 1; Table 6) indicating some significant moderation. Table 5 shows significant interaction parameters in the full moderation model for the means, shared environment, and nonshared environment. All the models that dropped moderation on C and the one that dropped moderation on E only (Models 5, 6, 7, and 9; Table 6) showed a significant decrement in fit. The AICs for the full moderation model (Model 1), moderation on means, C and E model (Model 4), and moderation on means and C (Model 8) were all very similar, however, Model 4 had the lowest AIC and was selected as the best-fitting model.

DISCUSSION

The current paper set out to investigate whether SES moderates the genetic and environmental variance in reading in a diverse elementary-aged twin sample. Six SES variables were modeled separately to test for such moderating effects. One of the most consistent findings was the moderating effect on the means of reading by the SES variables such that as SES disadvantage increased reading scores decreased. This finding is well-documented in the phenotypic literature. However, of greater interest using this genetically sensitive twin design was whether SES moderated genetic and environmental variance on reading and these results were somewhat less straightforward with regard to the significance of effects and the trends of the best-fitting models. Though the full moderation models show a trend for slightly increasing genetic variance across levels of the SES moderators in five of the six SES variables, these interaction parameter estimates never reached significance nor were they included in five of the six best-fitting models. Thus, based on these results there was no evidence of gene X SES interactions.

In contrast, there was more consistent evidence of a shared environment X SES interaction. The full moderation models show a decrease in shared environmental variance across levels of the SES moderators in all of the SES variables. While the shared environment interaction parameters were significant for just two of the SES variables, the best-fitting models included shared environmental moderation in four of the six SES variables. Additionally, there was a trend for a slight decrease in nonshared environmental variance across levels of the SES moderators which were mostly nonsignificant.

Overall, there was more total variance in reading at lower levels of SES. This increase at lower SES was primarily due to an increase in shared environmental variance. There are many potential environmental risk factors that children of low-SES families are exposed to more so than their higher-SES counterparts. For example, a recent review found that they are exposed to more instability, violence, and chaotic households (Evans, 2004). They tend to receive less social support, are read to less frequently, have less access to books, watch more television, attend poorer performing schools, and live in more dangerous neighborhoods. Given the many sources of environmental disadvantage that affect children of lower SES, it is not surprising that they show significantly more shared environmental variance compared to their higher SES counterparts.

Some research has indicated that each of the three traditional components of SES uniquely measures aspects of SES (Bradley & Corwyn, 2002). As such, each of the SES variables was modeled separately in order to understand whether particular aspects of SES had the same impact on the etiological sources of variance. Though there were some similar trends in the results, the magnitudes varied and the presence of trends was not uniform. Inconsistencies in the moderation results across the SES variables may stem from the aspects of SES they measure and their differential relationship with reading. For example, there appears to be some aspect of the environment that is captured in the Parental Occupation variable that is not captured in the Parental Education or Household Income variables that moderates genetic and environmental variance in reading to a greater degree. This may initially seem surprising given the lower phenotypic correlation of Parental Occupation with reading, however, it is important to remember that the effect of the SES moderator on the mean of reading scores was been partialed out for these models and only the residualized variance was decomposed into genetic and environmental influences. Differing results across the SES variables may also reflect how sensitively they capture the SES environment. The more distal measures of SES, FRL and Neighborhood Income, had weaker interaction effects than the more proximal SES measures, suggesting that they may have been unable to capture aspects of SES that moderate genetic and environmental influences on reading to the same extent as the more proximal measures.

The timing of when reading and the SES variables were measured may also be impacting findings. The large majority of twin pairs in the current study were measured on reading in third grade, but some twins were measured in fourth or fifth grade. The relationship between SES and various outcomes has been shown to change across different developmental stages throughout childhood (Chen, Matthews & Boyce, 2002). Studies have shown that some G x E interactions are age sensitive (Lenroot & Giedd, 2011) and Grant and colleagues (2010) have suggested that G x SES effects may be affected by critical periods. If G x SES interaction effects are limited to particular developmental stages then the strength of the effect may have been weakened by including twins at multiple developmental stages in reading. If so, this may have contributed to observed trends failing to reach statistical significance.

Another aspect of measurement timing concerns the amount of time between measurement of reading and SES. Reading data were collected using a cross-sectional design across the 2005-2006 through 2010-2011 school years. The FRL variable was measured at the same time as reading, but for all other SES variables the time between measurement of reading and measurement of the SES variables was not simultaneous. All Neighborhood Income data were collected in 1999 as part of the U.S. Census and, though this is the most recently available estimate of neighborhood SES, the time between its collection and assessment of reading was six to twelve years later. Parental Education, Parental Occupation, and Household Income variables were collected in 2010 and the time between assessment of reading and collection of these SES variables ranged from zero to four years. To the extent that the SES circumstances were different when reading was measured versus when SES was measured, the true effects of SES on reading may not be represented in the results. It is also the case that these SES measures represent a single snapshot in time of socioeconomic circumstances. Research has shown that persistent poverty appears to have a greater negative impact on children (Evans, 2004). If SES responses (e.g., low household income or unemployment) reflected more temporary circumstances of the economic downturn for some families while more persistent circumstances for other families then these differential circumstances would not be reflected in the SES measures and moderation effects may have been weakened.

It was hypothesized that moderation results would be consistent with the bioecological model (Bronfenbrenner & Ceci, 1994) which proposes that genetic variance increases as environmental advantage increases. The genetic variance in the current study was not significantly different across SES and therefore results did not support the bioecological model. Interestingly, if standardized (i.e., proportional) estimates of variance were relied upon (as has been the case in several studies) rather than unstandardized estimates to determine support of the theory then the opposite conclusion would have been drawn. In contrast to the bioecological model, Scarr’s (1992) theory postulates lower genetic variability only at extreme deprivation and no differences across the normal range of rearing environments. The observed lack of significant genetic moderation on reading does support the part of Scarr’s theory that proposes no genetic variance differences in normal range rearing environments.

Though this is the first known study to investigate moderating effects of SES on reading across the range of ability in children using a continuous moderation model, such studies have been conducted on IQ that can offer some comparison. SES moderated both genetic and shared environmental influences on IQ at age 2 (Tucker-Drob et al., 2011) and age 7 (Turkheimer et al., 2003), just shared environmental influences from ages 2-14 (Hanscombe et al., 2012), and just genetic influences at age 17 (Harden et al., 2007). Though the etiological sources driving moderation were not entirely consistent across studies, moderation trends were observed in all studies and, as in the current study, it was consistently the case that any observed increases in genetic variance were associated with higher SES and increases in environmental variance were associated with lower SES.

In the only other continuous moderation SEM study on reading, the same pattern of moderation on shared environmental effects but no moderation on genetic effects found in the current study was also found for word reading in adults (Kremen et al., 2005). There was also more shared environmental influence at lower SES and more genetic influences at middle- and higher SES in a multigroup SEM study on oral reading fluency in first grade (Taylor & Schatschneider, 2010). Just one extant study that tested moderation across the range of reading ability, a study of 10-20-year olds using a regression approach (Kirkpatrick et al., 2011), has failed to detect any moderating effects. Unlike reading, prereading skills do not tend to show moderation. No moderation was found on prereading skills in preschool (Rhemtulla & Tucker-Drob, 2012) nor in two of three prereading skills tested in a kindergarten sample (Taylor & Schatschneider, 2010). Overall, findings across studies suggest that SES does moderate etiological influences on both IQ and reading in children.

A potential limitation of the current study is the sample size available, particularly for the more proximal SES variables, Parental Education, Parental Occupation, Household Income, and Barratt/Hollingshead SES. The sample sizes may not have been adequate given the power demands of the analyses. Despite the fact that continuous moderation SEM analyses are more powerful than heterogeneity analyses with artificial dichotomization or regression analyses (Purcell, 2002), a recent simulation demonstrated that the sample sizes to detect effects may be quite high (Hanscombe et al., 2012). Another limitation of the current study is that reading and SES data were not available for all twins and analyses of missing data showed that missingness was associated with disadvantage. Much of the missingness was due to the nature of data collection and the combination of both longitudinal and cross-sectional designs of the study. Nonetheless, a different pattern of results may have emerged had data been available for these twins. Additionally, moderation results should be interpreted with caution given that observed effects were not consistently significant for both parameter estimates with 95% CIs and model comparisons. Further studies with larger sample sizes are necessary to test whether such effects are detected within acceptable levels of chance.

In conclusion, there was no significant gene X SES interaction for reading in a diverse elementary-aged twin sample, but there was a significant shared environment X SES interaction for some of the SES variables. Lower SES families had more total variance in reading and the source of this increased variance was shared environmental experiences. Some SES variables showed greater moderation than others suggesting that particular aspects of SES differentially affect variability in reading. It well-established that SES is related to reading proficiency and studies such as the current one that provide evidence that etiological sources of variance in reading are impacted to a greater degree by some aspects of SES more so than others offers opportunities for future studies to investigate more specific factors to be targeted for potential interventions. Furthermore, given that children in low-SES families have greater variability in reading due to environmental sources compared to their higher-SES peers, it seems that this population would especially benefit from environmental interventions.

APPENDIX A

TABLES

Table 1

Means and Standard Deviations of Reading and SES Variables for Twins with Available Data versus Twins with Missing Data.

	Reading			Free/Reduced-Price Lunch			Neighborhood Income			Parental Education			Parental Occupation			Household Income			Barratt/Hollingshead SES		
	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N
Reading																					
Available	326.24	58.13	3366	52.01%	0.50	3188	$42,569.71	$14,146.84	2766	4.86	1.55	887	4.72	3.07	870	4.01	1.59	876	39.86	16.27	831
Missing	---	---	---	0	0	0	$42,436.30	$13,593.01	1106	4.67	1.67	423	4.06	3.11	410	3.76	1.69	434	36.09	16.85	387
Free/Reduced-Price Lunch																					
Available	327.28	57.77	3188	52.01%	0.50	3188	$42,684.69	$14,118.99	2612	4.85	1.55	852	4.76	3.04	836	4.03	1.59	842	40.01	16.16	800
Missing	307.69	61.49	178	---	---	---	$42,214.26	$13,716.53	1260	4.70	1.67	458	4.04	3.15	444	3.74	1.67	468	36.07	16.96	418
Neighborhood Income																					
Available	326.95	58.05	2766	52.30%	0.50	2612	$42,531.60	$13,989.26	3872	4.84	1.64	1044	4.54	3.08	1006	3.94	1.66	1040	38.91	16.55	960
Missing	322.95	58.42	600	50.69%	0.50	576	---	---	---	4.64	1.39	266	4.39	3.15	274	3.88	1.49	270	37.73	16.52	258
Parental Education																					
Available	336.40	54.17	887	45.54%	0.50	852	$43,395.32	$13,527.38	1044	4.80	1.59	1310	4.63	3.07	1218	3.97	1.62	1250	38.66	16.54	1218
Missing (Non-response)	313.62	57.12	1229	62.18%	0.49	1158	$41,549.74	$13,885.82	1494	---	---	---	2.19	2.76	62	3.10	1.71	60	0	0	0
Parental Occupation																					
Available	335.00	54.89	870	45.45%	0.50	836	$43,257.55	$13,332.02	1006	4.87	1.56	1218	4.51	3.10	1280	3.99	1.60	1226	38.66	16.54	1218
Missing (Non-response)	314.91	57.03	1246	62.01%	0.49	1174	$41,685.99	$14,014.42	1532	3.82	1.71	92	---	---	---	2.98	1.82	84	0	0	0
Household Income																					
Available	334.88	55.32	876	46.08%	0.50	842	$43,217.78	$13,709.19	1040	4.81	1.58	1250	4.58	3.08	1226	3.93	1.63	1310	39.03	16.46	1166
Missing (Non-response)	314.89	56.76	1240	61.64%	0.49	1168	$41,677.93	$13,776.02	1498	4.45	1.73	60	2.89	3.12	54	---	---	---	30.40	16.44	52
Barratt/Hollingshead SES																					
Available	336.93	54.17	831	44.00%	0.50	800	$43,540.68	$13,328.22	960	4.87	1.56	1218	4.63	3.07	1218	4.04	1.58	1166	38.66	16.54	1218
Missing (Non-response)	314.27	57.05	1285	62.48%	0.48	1210	$41,559.56	$13,978.09	1578	3.82	1.71	92	2.19	2.76	62	3.03	1.77	144	---	---	---

Note . Free/Reduced-Price Lunch is the percentage of twins receiving Free/Reduced-Price Lunch. Ns refer to individuals. Descriptive statistics for Reading, Free/Reduced-Price Lunch, and Neighborhood Income for "Missing (Non-response)" Parental Education, Parental Occupation, Household Income, and Barratt/Hollingshead SES variables include only twin families who were recruited to participate in the questionnaire study but did not respond.

Table 2

Means and Standard Deviations of SES moderators, Reading, and Reading by levels of the SES Moderators in the Total Sample and by Zygosity

	MZ			DZ			Total Sample		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
Free/Reduced-Price Lunch	-0.126	0.987	1098	0.069	1.000	2084	0.002	1.000	3182
Reading	-0.085	0.974	1098	0.070	0.999	2084	0.016	0.993	3182
FRL	-0.379	0.938	640	-0.279	0.926	1012	-0.318	0.931	1652
No FRL	0.326	0.871	458	0.399	0.953	1072	0.377	0.929	1530
Neighborhood Income	-0.005	1.003	950	0.009	1.022	1886	0.004	1.015	2836
Reading	-0.074	0.961	930	0.043	1.015	1832	0.004	0.999	2762
-2 N. Income	-0.296	0.603	13	-0.390	0.896	36	-0.365	0.823	49
-1 N. Income	-0.304	1.014	274	-0.191	0.985	548	-0.229	0.995	822
0 N. Income	-0.076	0.892	444	0.081	1.002	806	0.025	0.967	1250
1 N. Income	0.155	0.942	140	0.175	1.012	325	0.169	0.991	465
2 N. Income	0.516	0.970	59	0.647	0.941	117	0.603	0.950	176
Parental Education	0.020	0.988	452	0.053	0.961	444	0.037	0.974	896
Reading	0.138	0.898	448	0.208	0.957	439	0.173	0.928	887
-2 Parental Educ.	-0.374	0.681	17	-0.342	0.993	14	-0.359	0.822	31
-1 Parental Educ.	-0.149	0.889	158	-0.171	0.973	153	-0.160	0.930	311
0 Parental Educ.	0.221	0.956	145	0.254	0.827	118	0.236	0.899	263
1 Parental Educ.	0.412	0.784	90	0.574	0.902	128	0.507	0.857	218
2 Parental Educ.	0.600	0.504	38	0.722	0.666	26	0.649	0.574	64

Table 2, continued

Parental Occupation	0.150	0.982	440	-0.024	0.997	442	0.062	0.993	882
Reading	0.119	0.915	435	0.176	0.970	435	0.147	0.943	870
-2 Parental Occup.	(empty cell)			(empty cell)			(empty cell)		
-1 Parental Occup.	0.130	1.078	98	-0.176	1.062	125	-0.042	1.078	223
0 Parental Occup.	-0.109	0.833	140	0.164	0.937	139	0.027	0.896	279
1 Parental Occup.	0.275	0.851	197	0.444	0.838	171	0.353	0.848	368
2 Parental Occup.	(empty cell)			(empty cell)			(empty cell)		
Household Income	0.025	0.963	450	0.072	1.000	438	0.048	0.981	888
Reading	0.098	0.930	445	0.195	0.965	431	0.146	0.948	876
-2 H. Income	-0.304	0.935	25	-0.488	1.085	20	-0.386	0.997	45
-1 H. Income	-0.141	1.029	161	-0.161	0.962	170	-0.151	0.994	331
0 H. Income	0.013	0.918	84	0.380	0.747	55	0.158	0.871	139
1 H. Income	0.417	0.728	175	0.540	0.861	186	0.480	0.800	361
2 H. Income	(empty cell)			(empty cell)			(empty cell)		
Barratt/Hollingshead SES	0.157	0.964	418	-0.017	0.998	422	0.070	0.984	840
Reading	0.158	0.900	414	0.204	0.959	417	0.181	0.930	831
-2 SES	0.262	1.196	29	-0.608	0.955	43	-0.257	1.135	72
-1 SES	0.133	0.940	79	0.142	0.993	93	0.138	0.967	172
0 SES	-0.085	0.828	113	0.200	0.940	110	0.056	0.895	223
1 SES	0.275	0.857	183	0.439	0.843	167	0.353	0.853	350
2 SES	0.645	0.575	10	0.710	0.378	4	0.663	0.513	14

Note. MZ = monozygotic; DZ = dizygotic. SES moderator and Reading means for all twins with data available on each moderator are given in the first rows of the table followed by means within the different levels (in standard deviation units) of the SES moderators (e.g., 0 N. Income includes those between -.5 and .5 SDs from the mean, 1 N. Income includes those between .5 and 1.5 SDs from the mean, etc.). Lower levels of the SES moderators indicate greater socioeconomic disadvantage. Ns refer to individuals.

Table 3

Phenotypic Correlations between Reading and SES Variables

Variable		1	2	3	4	5	6	7
1	Reading	---						
2	Free/Reduced-Price Lunch	-0.356	---					
	N	1591						
3	Neighborhood Income	0.225	-0.372	---				
	N	1379	1306					
4	Parental Education	0.322	-0.488	0.334	---			
	N	444	426	522				
5	Parental Occupation	0.178	-0.353	0.199	0.328	---		
	N	436	418	503	609			
6	Household Income	0.313	-0.668	0.376	0.490	0.385	---	
	N	439	421	520	625	613		
7	Barratt/Hollingshead SES	0.185	-0.390	0.226	0.480	0.985	0.431	---
	N	416	400	480	609	609	583	

Note. Correlations based on one randomly selected twin from each twin pair. All correlations significant at $p < .001$.

Table 4

Intraclass Correlations of Reading by Zygosity at Different Levels of the SES Moderators

	MZ		DZ	
	Intraclass *r*	N pairs	Intraclass *r*	N pairs
Free/Reduced-Price Lunch				
Reading	0.772	549	0.459	1042
FRL	0.740	320	0.434	506
No FRL	0.735	229	0.348	536
Neighborhood Income				
Reading	0.764	455	0.465	889
-2 N. Income	0.432	6	0.650	17
-1 N. Income	0.790	134	0.455	266
0 N. Income	0.686	218	0.412	393
1 N. Income	0.826	68	0.450	156
2 N. Income	0.835	29	0.453	57
Parental Education				
Reading	0.719	222	0.498	217
-2 Parental Educ.	0.715	8	0.643	7
-1 Parental Educ.	0.681	78	0.451	76
0 Parental Educ.	0.743	72	0.601	59
1 Parental Educ.	0.666	45	0.243	62
2 Parental Educ.	0.241	19	0.177	13
Parental Occupation				
Reading	0.718	215	0.513	214
-2 Parental Occup.	(empty cell)		(empty cell)	
-1 Parental Occup.	0.722	48	0.642	61
0 Parental Occup.	0.624	69	0.408	68
1 Parental Occup.	0.754	98	0.353	85
2 Parental Occup.	(empty cell)		(empty cell)	

Table 4, continued

Household Income				
Reading	0.732	220	0.517	212
-2 H. Income	0.604	11	0.143	10
-1 H. Income	0.702	80	0.508	84
0 H. Income	0.794	42	0.486	27
1 H. Income	0.676	87	0.392	91
2 H. Income	(empty cell)		(empty cell)	
Barratt/Hollingshead SES				
Reading	0.705	205	0.500	206
-2 SES	0.757	14	0.435	21
-1 SES	0.634	39	0.654	46
0 SES	0.618	56	0.350	55
1 SES	0.757	91	0.359	82
2 SES	(nearly empty cell)		(nearly empty cell)	

Note. MZ = monozygotic; DZ = dizygotic. The intraclass correlations for Reading are reported within the different levels (in standard deviation units) of the SES moderators (e.g., 0 N. Income includes those between -.5 and .5 SDs from the mean, 1 N. Income includes those between .5 and 1.5 SDs from the mean, etc.). Lower levels of the SES moderators indicate greater socioeconomic disadvantage. The number of pairs in this table reflect only pairs in which Reading was available for both pairs, however, pairs in which at least one twin with Reading were used in the formal moderation analyses using full-information maximum likelihood.

Table 5

Genetic and Environmental Parameter Estimates and 95% Confidence Intervals for Reading Moderated by SES for the Standard ACE, Full Moderation, and Best-Fitting Models for each SES Variable

	Standard ACE Model		Full Moderation Model		Best-Fitting Model	
Parameter	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Free/Reduced-Price Lunch						
a	**0.799**	(0.733, 0.863)	**0.767**	(0.711, 0.820)	**0.796**	(0.730, 0.839)
c	**0.365**	(0.192, 0.476)	0.180	(0, 0.335)	0.134	(0, 0.325)
e	**0.466**	(0.440, 0.495)	**0.469**	(0.442, 0.498)	**0.467**	(0.440, 0.496)
β_M	[0]		**-0.347**	(-0.387, -0.307)	**-0.346**	(-0.386, -0.307)
β_X	[0]		-0.049	(-0.103, 0.004)	[0]	
β_Y	[0]		0.173	(-0.199, 0.330)	[0]	
β_Z	[0]		0.008	(-0.020, 0.035)	[0]	
Neighborhood Income						
a	**0.805**	(0.733, 0.874)	**0.805**	(0.734, 0.873)	**0.811**	(0.740, 0.880)
c	**0.379**	(0.195, 0.496)	0.306	(0, 0.439)	0.293	(0, 0.432)
e	**0.466**	(0.437, 0.498)	**0.464**	(0.435, 0.496)	**0.463**	(0.435, 0.495)
β_M	[0]		**0.220**	(0.175, 0.266)	**0.218**	(0.174, 0.261)
β_X	[0]		0.027	(-0.022, 0.080)	[0]	
β_Y	[0]		-0.035	(-0.143, 0.067)	[0]	
β_Z	[0]		-0.032	(-0.058, 0.004)	-0.024	(-0.051, 0.008)
Parental Education						
a	**0.666**	(0.522, 0.800)	**0.661**	(0.519, 0.784)	**0.641**	(0.506, 0.752)
c	**0.443**	(0.137, 0.602)	0.330	(0, 0.515)	**0.362**	(0.089, 0.525)
e	**0.477**	(0.436, 0.526)	**0.478**	(0.437, 0.526)	**0.480**	(0.438, 0.528)
β_M	[0]		**0.309**	(0.236, 0.383)	**0.310**	(0.236, 0.385)
β_X	[0]		-0.032	(-0.121, 0.064)	[0]	
β_Y	[0]		-0.075	(-0.202, 0.117)	-0.100	(-0.211, 0.009)
β_Z	[0]		-0.007	(-0.051, 0.040)	[0]	

Table 5, continued

Parental Occupation						
a	**0.654**	(0.502, 0.792)	**0.638**	(0.459, 0.754)	**0.638**	(0.459, 0.754)
c	**0.490**	(0.236, 0.642)	**0.355**	(0.070, 0.566)	**0.355**	(0.070, 0.566)
e	**0.482**	(0.440, 0.532)	**0.485**	(0.442, 0.535)	**0.485**	(0.442, 0.535)
β_M	[0]		**0.176**	(0.090, 0.262)	**0.176**	(0.090, 0.262)
β_X	[0]		0.113	(-0.020, 0.277)	0.113	(-0.020, 0.277)
β_Y	[0]		**-0.316**	(-0.478, -0.139)	**-0.316**	(-0.478, -0.139)
β_Z	[0]		-0.040	(-0.087, 0.005)	-0.040	(-0.087, 0.005)
Household Income						
a	**0.653**	(0.503, 0.791)	**0.660**	(0.497, 0.798)	**0.665**	(0.528, 0.777)
c	**0.504**	(0.261, 0.654)	0.375	(0, 0.557)	**0.370**	(0.0270, 0.548)
e	**0.478**	(0.436, 0.527)	**0.475**	(0.434, 0.524)	**0.474**	(0.434, 0.522)
β_M	[0]		**0.323**	(0.246, 0.399)	**0.323**	(0.246, 0.399)
β_X	[0]		0.010	(-0.114, 0.142)	[0]	
β_Y	[0]		-0.103	(-0.330, 0.255)	-0.091	(-0.326, 0.033)
β_Z	[0]		**-0.064**	(-0.112, -0.015)	**-0.062**	(-0.104, -0.020)
Barratt/Hollingshead SES						
a	**0.647**	(0.489, 0.789)	**0.630**	(0.459, 0.758)	**0.680**	(0.534, 0.780)
c	**0.461**	(0.170, 0.620)	**0.391**	(0.109, 0.570)	**0.355**	(0.043, 0.556)
e	**0.490**	(0.445, 0.542)	**0.492**	(0.448, 0.544)	**0.486**	(0.444, 0.536)
β_M	[0]		**0.180**	(0.095, 0.265)	**0.186**	(0.104, 0.270)
β_X	[0]		0.084	(-0.041, 0.234)	[0]	
β_Y	[0]		**-0.227**	(-0.387, -0.058)	**-0.159**	(-0.376, -0.031)
β_Z	[0]		**-0.047**	(-0.095, -0.0004)	-0.035	(-0.080, 0.008)

Note. The a, c, and e parameters are the main effects of genes, shared environment, and non-shared environment, respectively. The β_M, β_X, β_Y, and β_Z parameters are the moderation effects on reading means, genes, shared environment, and non-shared environment, respectively. Bolded parameters are significant at $p < .05$.

Table 6

Model Fit Statistics of Models Testing for Moderation on Reading by SES Variables

Model	-2LL	df	AIC	-2LLΔ	dfΔ	p-val.
Free/Reduced-Price Lunch						
1. Full Moderation	7957.98	3174	1609.98			
2. No Moderation	8232.10	3178	1876.10	274.124	4	< .001
3. Moderated Means	**7961.70**	**3177**	**1607.70**	**3.719**	**3**	**0.293**
4. Moderation on Means, C and E	7961.32	3175	1611.32	3.337	1	0.068
5. Moderation on Means, A and E	7961.31	3175	1611.31	3.333	1	0.068
6. Moderation on Means, A and C	7958.28	3175	1608.28	0.299	1	0.585
7. Moderation on Means and A	7961.34	3176	1609.34	3.366	2	0.186
8. Moderation on Means and C	7961.39	3176	1609.39	3.412	2	0.182
9. Moderation on Means and E	7961.68	3176	1609.68	3.704	2	0.157
Neighborhood Income						
1. Full Moderation	7115.60	2754	1607.60			
2. No Moderation	7209.67	2758	1693.67	94.062	4	< .001
3. Moderated Means	7118.99	2757	1604.99	3.389	3	0.335
4. Moderation on Means, C and E	7116.75	2755	1606.75	1.15	1	0.284
5. Moderation on Means, A and E	7116.09	2755	1606.09	0.49	1	0.484
6. Moderation on Means, A and C	7118.73	2755	1608.73	3.124	1	0.077
7. Moderation on Means and A	7118.99	2756	1606.99	3.389	2	0.184
8. Moderation on Means and C	7118.83	2756	1606.83	3.224	2	0.199
9. Moderation on Means and E	**7116.77**	**2756**	**1604.77**	**1.168**	**2**	**0.558**
Parental Education						
1. Full Moderation	2091.94	879	333.94			
2. No Moderation	2159.74	883	393.74	67.805	4	< .001
3. Moderated Means	2095.99	882	331.99	4.055	3	0.256
4. Moderation on Means, C and E	2092.38	880	332.38	0.448	1	0.503
5. Moderation on Means, A and E	2093.05	880	333.05	1.116	1	0.291
6. Moderation on Means, A and C	2092.01	880	332.01	0.077	1	0.781
7. Moderation on Means and A	2093.11	881	331.11	1.176	2	0.555
8. Moderation on Means and C	**2092.68**	**881**	**330.68**	**0.748**	**2**	**0.688**
9. Moderation on Means and E	2095.31	881	333.31	3.369	2	0.186

Table 6, continued

Parental Occupation						
1. Full Moderation	**2109.48**	**862**	**385.48**			
2. No Moderation	2142.96	866	410.96	33.477	4	< .001
3. Moderated Means	2126.46	865	396.46	16.981	3	0.001
4. Moderation on Means, C and E	2112.35	863	386.35	2.868	1	0.090
5. Moderation on Means, A and E	2119.42	863	393.42	9.935	1	0.002
6. Moderation on Means, A and C	2112.48	863	386.48	2.999	1	0.083
7. Moderation on Means and A	2120.72	864	392.72	11.239	2	0.004
8. Moderation on Means and C	2113.82	864	385.82	4.343	2	0.114
9. Moderation on Means and E	2122.56	864	394.56	13.079	2	0.001
Household Income						
1. Full Moderation	2078.11	868	342.11			
2. No Moderation	2156.28	872	412.28	78.168	4	< .001
3. Moderated Means	2091.23	871	349.23	13.122	3	0.004
4. Moderation on Means, C and E	**2078.13**	**869**	**340.13**	**0.024**	**1**	**0.877**
5. Moderation on Means, A and E	2079.06	869	341.06	0.946	1	0.331
6. Moderation on Means, A and C	2084.56	869	346.56	6.449	1	0.011
7. Moderation on Means and A	2084.64	870	344.64	6.526	2	0.038
8. Moderation on Means and C	2086.38	870	346.38	8.271	2	0.016
9. Moderation on Means and E	2080.29	870	340.29	2.18	2	0.336
Barratt/Hollingshead SES						
1. Full Moderation	2004.16	823	358.16			
2. No Moderation	2035.47	827	381.47	31.31	4	< .001
3. Moderated Means	2016.99	826	364.99	12.839	3	0.005
4. Moderation on Means, C and E	**2005.89**	**824**	**357.89**	**1.73**	**1**	**0.188**
5. Moderation on Means, A and E	2010.16	824	362.16	6.001	1	0.014
6. Moderation on Means, A and C	2008.07	824	360.07	3.914	1	0.048
7. Moderation on Means and A	2012.54	825	362.54	8.381	2	0.015
8. Moderation on Means and C	2008.43	825	358.43	4.273	2	0.118
9. Moderation on Means and E	2011.97	825	361.97	7.819	2	0.020

Note. A = genetic variance; C = shared environmental variance; E = nonshared environmental variance; AIC = Akaike's Information Criterion; -2LLΔ = the chi-square change between the full moderation model and reduced models. The best-fitting model for each SES variable is indicated in bold type.

APPENDIX B

FIGURES

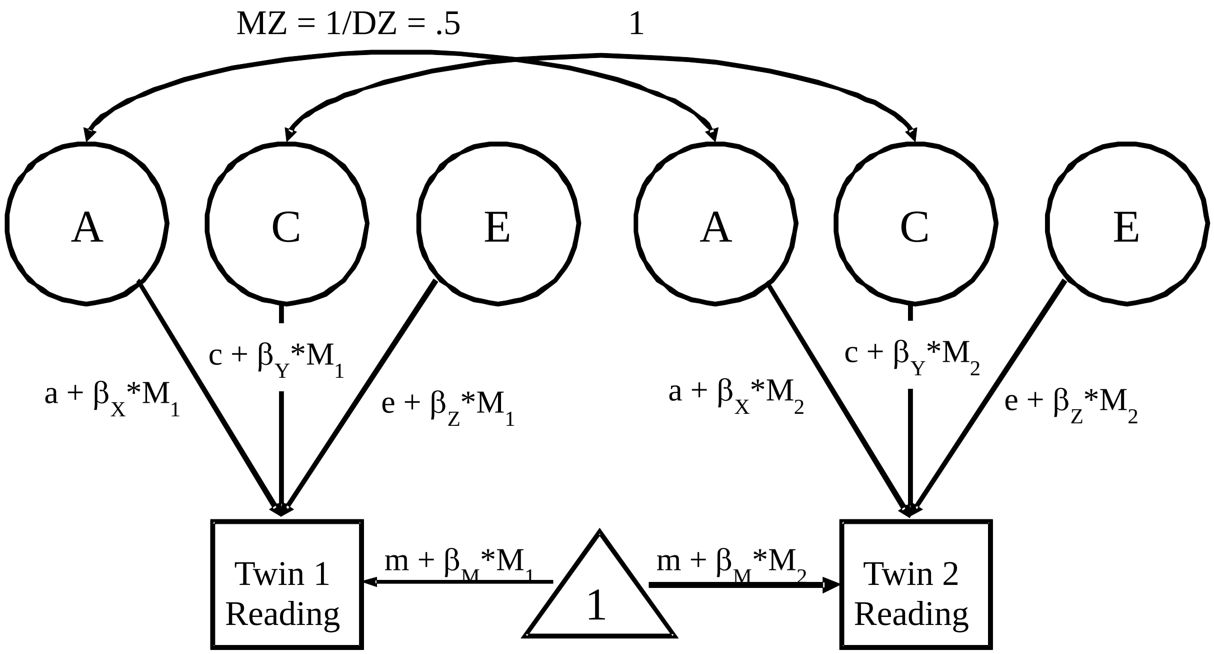

Figure 1. The Moderated ACE Model. Rectangles = measured twin 1 and twin 2 reading scores. Circles = latent influences of genetic (A), shared environment (C), and nonshared environment (E) on variation in reading scores. Parameters a, c, and e denote the parts of variance unrelated to the moderator. M = the measured moderator. Parameters β_X, β_Y, and β_Z denote parts of the variance that depend on the moderator. Triangle = mean reading scores. Parameter m denotes the part of the mean unrelated to the moderator and β_M denotes the part of the mean that depends on the moderator.

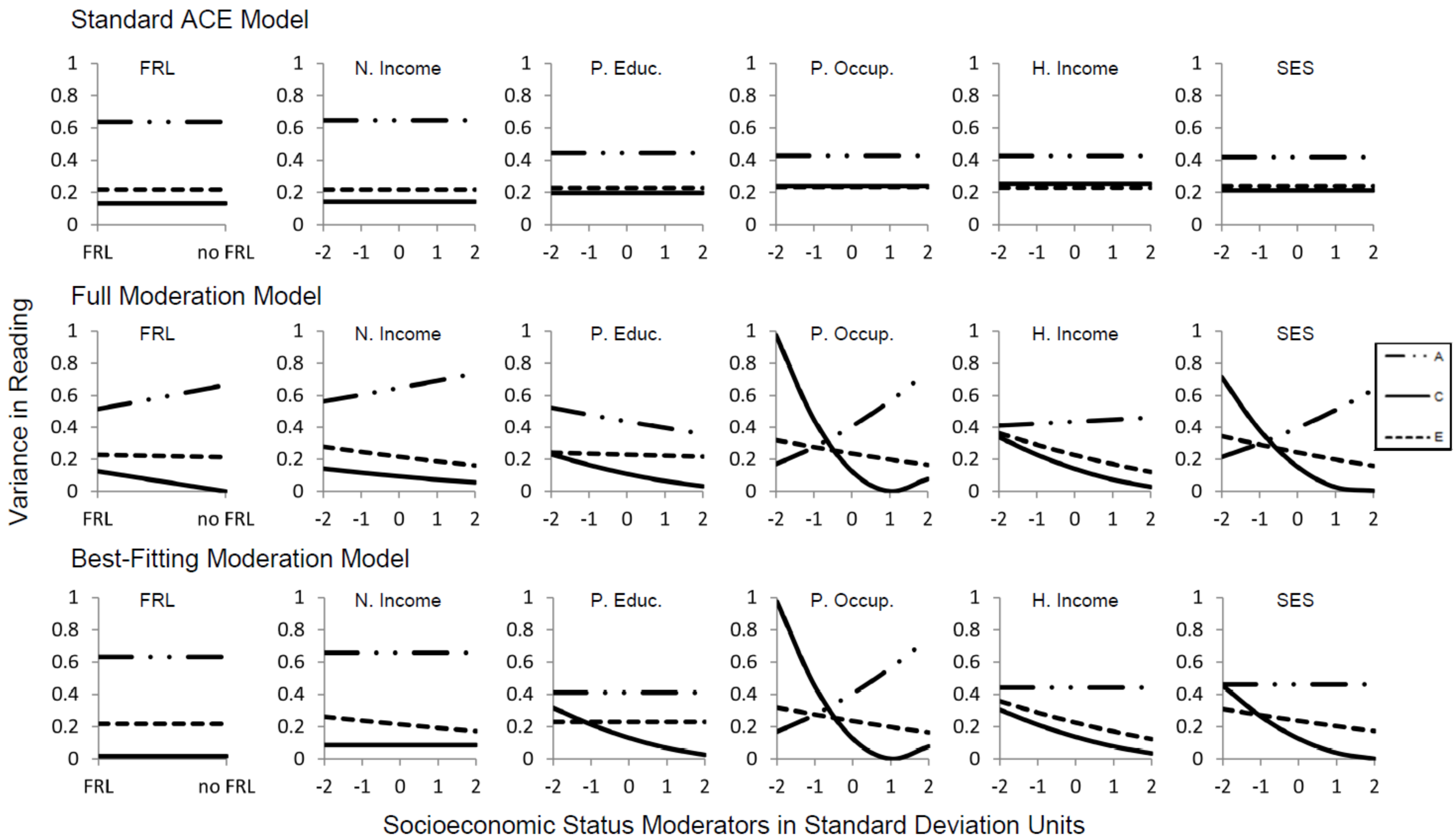

Figure 2. Unstandardized genetic and environmental variance components in Reading as a function of socioeconomic status moderators. The top row shows the standard ACE model (no moderation model). The second row shows the full moderation model in which all moderation components are modeled. The bottom row shows the best-fitting moderation model chosen by the lowest AIC. FRL = Free or Reduced-Price Lunch; N. Income = Neighborhood Income; P. Educ. = Parental Education; P. Occup. = Parental Occupation; H. Income = Household Income; SES = Barratt/Hollingshead SES; A = genetic variance; C = shared environmental variance; E = nonshared environmental variance.

APPENDIX C

SES QUESTIONNAIRE ITEMS

Florida Twin Project parental education (note: this was asked as two separate questions, one for the biological mother and one for the biological father), income, and occupation questions.

What is the highest level of education for the twins' **biological mother/father** (check one):

___ Grade 6 or less
___ Grade 7-12 (without graduating high school or equivalent)
___ Graduated high school or high school equivalent
___ Some college
___ Graduated from 2-year college
___ Graduated from 4-year college
___ Attended graduate or professional school without graduating
___ Completed graduate or professional school
___ Don't know

What is your occupation? ____

What is the *current* **household income** for the twins? (check one)

___ less than $10,000
___ $10,000 – 29,000
___ $30,000 – 49,000
___ $50,000 – 69,000
___ $70,000 – 89,000
___ $90,000 or more
___ Don't know

Hollingshead Level of School Completed	**Florida Twin Project Education Response Equivalent**
Less than seventh grade	Grade 6 or less
Junior high school (9th grade)	
Partial high school (10th or 11th grade)	Grade 7-12 (without graduating high school or equivalent)
High school graduate	Graduated high school or high school equivalent
Partial college (at least one year) or specialized training	Some college; Graduated from 2-year college
Standard college or university graduation	Graduated from 4-year college; Attended graduate or professional school without graduating
Graduate professional training (graduate degree)	Completed graduate or professional school

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BIOGRAPHICAL SKETCH

Brooke Soden-Hensler graduated *summa cum laude* with a Bachelor of Arts in Psychology from Pacific Lutheran University in 2005. There she studied language acquisition under the advisement of Dr. Wendelyn Shore. She then went on to work at Carnegie Mellon University with Dr. Joseph Beck on the Project LISTEN computer reading tutor investigating automated assessment of word knowledge and reading comprehension. She began graduate studies in Cognitive Psychology at Florida State University in 2006 under the advisement of Dr. Chris Schatschneider. In 2010 she earned her Master of Science degree. Her graduate studies emphasized behavioral genetics and reading and were supported through an Institute of Education Sciences Predoctoral Interdisciplinary Research Training Fellowship at the Florida Center for Reading Research.