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Parental separation and children's genetic influences on education

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Abstract

Objective: This study focuses on the extent to which parental divorce and separation during childhood affect children's chances to realize genetic influences on educational attainment.

Background: Whether the family context matters for genetic influences on children's educational attainment remains an open question. Previous research mainly considers parents' socio-economic standing and overlooks a key dimension of social stratification: childhood family structure.

Method: This study draws on the US Health and Retirement Study (HRS) to estimate the association between education polygenic scores and educational attainment of adults who experienced a parental separation before age 16 compared to adults who lived continuously with both parents.

Results: Results show that genetic effects are smaller for adults whose parents separated compared to adults whose parents remained coupled. Moreover, additional analysis directed at the mechanisms provided no evidence that the negative impact of parental separation was attributable to adverse socioeconomic conditions during childhood.

Conclusion: The findings suggest that distinct inner-familial conditions linked to parental separation affect children's genetic influences on educational attainment.

KEYWORDS

biobehavioral processes, death, divorce, education, family structure, separation

INTRODUCTION

Decades of research have focused on how family instability during childhood, especially parental separation, negatively affects children's educational outcomes (Amato, 2010; Lee & McLanahan, 2015; Raley & Sweeney, 2020). Not only is children's educational success affected by social resources associated with parental socioeconomic status or childhood family structure, but also by children's genes (Belsky et al., 2016; Lee et al., 2018; Liu, 2018). However, whether or to what extent genetic influences are realized is highly dependent on the environmental conditions that children encounter (Bronfenbrenner & Ceci, 1994). An established line of research has focused on the importance of parents' socio-economic standing and examined whether genetic influences on cognitive abilities and education are stronger for children that grow up in socioeconomically advantaged families (Baier & Lang, 2019; Conley et al., 2015; Erola et al., 2021; Lin, 2020). These studies argue that advantaged parents provide resource-rich environmental conditions that are tailored to children's needs and facilitate the realization of genetic influences on IQ (Rowe et al., 1999; Scarr-Salapatek, 1971). Yet, few studies have gone beyond dimensions of socioeconomic status as an indicator for children's (dis-)advantage to assess the increasingly important role of childhood family structure and instability.

Research on whether and how childhood family structure moderates the link between genes and educational attainment is scarce. Most studies in this area are interested in a genetically sensitive approach to estimating the causal effect of divorce on educational attainment (e.g., D'Onofrio et al., 2005, 2006, 2007; Guo et al., 2008; Nederhof et al., 2012; Waldman, 2007). A recent twin-based study showed that parental separation lowered the relative importance of genetic influences on children's school-related outcomes during middle childhood in Germany, a context with a strong welfare state, a highly differentiated educational system, and comparatively low divorce rates (Baier & Winkle, 2020). Despite the valuable insights of the study, these findings may not be transferable to other countries where divorce is more common, with weaker welfare institutions that provide less protection against the risks linked to divorce, or less stratified educational systems (DiPrete, 2002; Kreidl et al., 2017).

This article extends previous genetically sensitive studies by posing two research questions: First, are genetic influences on education smaller among adults who experienced a parental separation during childhood compared to those who grew up in stable two-parent families in the US? Therefore, attention is shifted to the US, as a liberal welfare state known for its high levels of social inequality and low levels of protection against the adverse consequences of life course risks, such as divorce (DiPrete, 2002). Our following research question is directed at the mechanisms linking parental separation and the importance of genes for education. Are potential differences in genetic influences on education among adults who experienced a parental separation during childhood and those who grew up in stable two-parent families driven by socioeconomic differences, the absence of a parent, or family instability?

In this study, we draw on molecular genetics and life history data from the US Health and Retirement Study (HRS) to empirically assess our research questions. Specifically, we estimate the impact of genes on educational attainment by regressing adults' years of education on their education polygenic score (PGS) by family structure. In general terms, the education PGS provides a weighted sum score of measured genetic factors that are correlated with educational attainment. We use retrospective life history data to estimate how genetic influences on education vary for adults who experienced a parental separation or divorce before age 16, adults who lost a parent before age 16, and adults who lived continuously with both parents until age 16. Then we adjust our models for a wide range of adversities during childhood to account for socioeconomic differences by family structure.

In line with previous research, we use parental death as a second reference category and investigate whether the importance of genetic influences on education among adults who experienced a parental death during childhood is more similar to adults who experienced a parental separation or to those who grew up in stable two-parent families. This comparison allows us to adjudicate whether mechanisms related to economic disadvantage, parental absence, or family instability are the driving force behind any family structure differences we might find.

Although the implications of genetically sensitive research are noted throughout the article and we aim to provide a nuanced and balanced discussion of the limitations and ethical considerations of this study. A supplemental FAQ document that addresses common questions and concerns can be found online.

THEORETICAL BACKGROUND

Genetic influences on education

A long line of genetically sensitive research has demonstrated that educational attainment is influenced to a non-negligible degree by genes (Branigan et al., 2013; Lee et al., 2018; Okbay et al., 2022). Heritability—the percentage of variation in an individual trait (i.e., phenotype) that is accounted for by genetic variance as opposed to environmental variance—is the most common population level indicator that reflects the genetic component to the variation of a trait. Estimates for the heritability of educational attainment range widely, but nearly all studies show moderate heritability (Branigan et al., 2013; Lee et al., 2018; Okbay et al., 2022).

Long the gold standard in behavioral genetic research, twin studies compare monozygotic and dizygotic twins to decompose the variance into an additive genetic component, a component attributable to common environmental factors, and an environmental component unique to each twin (see Plomin et al., 2008 for a discussion of so called ACE models). Recent twin studies with data covering a range of countries and cohorts generally find that genetic factors account for roughly 40% of the variation in educational attainment, usually measured as years of education (Branigan et al., 2013; Silventoinen et al., 2020).

Twin studies, however, do not measure genes directly but infer them via the degree of relatedness between twin pairs. This and other rather strong model assumptions may lead to biased heritability estimates from ACE and other twin models. Advances in molecular genetics have enabled researchers to base heritability estimates on measured rather than assumed genetic similarity. A common approach to estimate heritability in molecular genetics entails the creation of PGSs based on genome-wide association studies (GWAS). GWAS are used to locate single-nucleotide polymorphisms (SNPs)—markers of genetic variation—that are associated with a trait, such as educational attainment, and quantify the strength of that association in a given study population. A PGS can then be constructed to estimate an individual's risk or predisposition for a trait by summarizing the associations between all SNPs and the trait of interest. The most recent PGS for educational attainment accounts for up to 16% of the variation in years of education in a sample of roughly 3 million individuals (Okbay et al., 2022).

How genes influence educational attainment is the subject of active research, but educational attainment is considered to be a highly complex human trait that is affected by a large number of genetic influences via multiple direct and indirect pathways (see Freese, 2008). The relatively high heritability of educational attainment likely reflects not only cognitive ability or intelligence but also numerous genetically influenced traits that are related to educational attainment (Krapohl et al., 2014). These include correlates of educational attainment, such as self-efficacy, personality traits, and other behavioral traits.

Importantly and of particular interest for social scientists, the heritability of educational attainment is not fixed but has been shown to vary across social contexts. Numerous studies have found such gene–environment interactions across countries and cohorts, that is, cross-national and cross-temporal variations in the influence of genes on education (Branigan et al., 2013; Heath et al., 1985; Herd et al., 2019; Lin, 2020).

However, the strength of genetic influences on education has been shown to vary across sub-populations within countries, in particular by the socioeconomic status of the parental home. To conceptualize how social conditions affect genetic influences on education, researchers often refer to the Scarr–Rowe hypothesis, which states that genetic effects on IQ are stronger in enriched social settings (Rowe et al., 1999; Scarr-Salapatek, 1971). The underlying mechanism linking enriched environments and genetic effects on IQ is thought to be enhancement, a mechanism that describes how resource-rich environments push individual development to its limits and foster the realization of genetic potential (Shanahan & Hofer, 2005). In contrast, resource-poor environmental conditions tend to suppress the development of genetic potential. The starting point of the Scarr–Rowe and enhancement mechanisms is the bio-ecological model, according to which humans develop in permanent exchange with environmental influences set by immediate environments, such as parents, but also more distal contextual levels, such as institutions (Bronfenbrenner & Ceci, 1994). Thus, whether or to what extent individuals realize their genetic endowments depends on specific aspects of the environment they encounter.

Previous research on the Scarr–Rowe hypothesis has mainly focused on cognitive ability, although recent studies shifted the focus to education. Empirical findings on educational outcomes are mixed. Twin-based studies provide support for a Scarr–Rowe Interaction (SRI) in Germany (Baier & Lang, 2019) and Finland (Erola et al., 2021). A recent study for Norway does not report any systematic variation in education PGS by parental social background (Isunget et al., 2021), while findings for the US remain mixed (Conley et al., 2015; Domingue et al., 2015; Lin, 2020). Divergent findings may be explained in light of methodological differences but also hint at the importance of the contextual differences between countries.

Parental Separation & Education

A more substantive limitation of this strand of research is the narrow focus on parents' structural stratification characteristics, such as parents' socio-economic standing, which neglects the pivotal role of household and demographic characteristics, such as family structure. Especially in the US, household income differences by family composition have become increasingly larger (McCall & Percheski, 2010), and family structure is now one of the main means through which inequalities are reproduced across generations (McLanahan & Percheski, 2008). To theorize about the relationship between parental separation and genetic influences on education, we first refer to the literature that theorizes about the mechanisms that link children's chances for educational success. In a second step, we use these insights to develop expectations about how family structure may shape genetic influences on children's educational attainment.

To date there are at least three major theoretical accounts explaining why family structure matters for children's educational success: the family instability, the parental absence, and the economic disadvantage perspectives (Amato, 2010; Biblarz & Gottainer, 2000). The family instability perspective concentrates on the adverse psychological consequences of separation (Cavanagh & Fomby, 2019). Accordingly, parental distress, conflict, and adverse living conditions linked to parents' separation affect family climate, create tension, and change how parents treat their children and parent–child relationships. Increased levels of stress and conflict lower a parent's capacity to provide emotional support and to respond adequately to children's socio-emotional needs. The resulting relationship instability and more distant parenting can increase behavioral problems and lower educational performance (Spera, 2005).

The parental absence perspective states that being raised with two parents in one household has advantages for children over living with one parent. Some have emphasized different socialization patterns between one- and two-parent households. For example, children may learn to internalize power dynamics and to adhere to rules better, because interactions with two parents are more often hierarchically structured than interactions with a single parent. Moreover, two parents have more time resources to provide better rearing conditions for children compared to a single parent. Specifically, this perspective adds the notion that it is more difficult for single parents to control children's enrichment activities and to monitor their educational progress compared to two-parent families due to both greater time constraints and a more limited social network. Previous research has shown that lower levels of parental monitoring may impede children's development and educational attainment (Fröjd et al., 2007; Kerr et al., 2010).

Lastly, the economic disadvantage perspective emphasizes that parents who separate tend to have a lower socio-economic standing than parents who stay together. In addition, this perspective emphasizes the economic consequences linked to a separation. Single parents have lower household income, and at the same time, they often have to reduce their time in the labor market due to increased child-care responsibilities. The resulting economic strain affects children's educational achievements for several reasons. It prevents parents from providing a stimulating home environment and good learning opportunities, which furthers the development of children's cognitive and non-cognitive skills and their academic progress (e.g., Cunha & Heckman, 2008). Additionally, more advantaged parents can afford better schools, private instructors, additional learning materials, and extra-curricular activities, also contributing to children's educational success.

Parental separation and genetic influences on education

Together, these three theoretical accounts propose different mechanisms that explain how the adverse consequences of separation affect children's educational outcomes. However, parental separation may not only be linked to children's education but also genetic influences of education (see Figure 1). Building on previous work (Baier & Van Winkle, 2021), we argue that parental separation and its related family processes and circumstances carry environmental features that can moderate genetic influences on education, that is, a gene–environment interaction

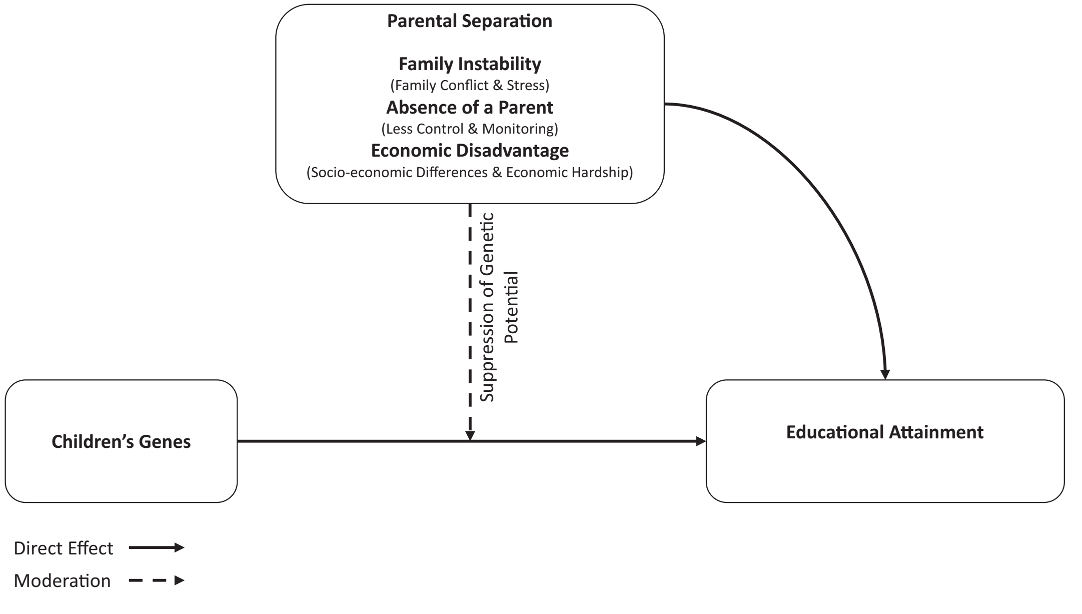

FIGURE 1 Conceptual framework: parental separation as moderator for genetic influences on educational attainment. *Source:* Adapted figure from Baier and Van Winkle (2021)

(GxE). This conceptual framework is about the variability of genetic factors and is thus far away from any notion of genetic determinism, highlighting the complex interplay between genes and the (family) environment.

Integrating the three main theoretical accounts—the family instability, the absence of a parent, and the economic disadvantage perspectives—we expect that parental separation impedes the enhancement mechanism for the following reasons (see Figure 1). First, separation triggers family stress and conflict which changes parental behavior and leads to lower emotional support and unstable parent–child relationships. Children that experience a separation are exposed to increased levels of stress for children, which are negatively linked to children's cognitive development and likely their related genetic influences (Lupien et al., 2009). Second, owing to time limitations and a loss in the social networks, single parents have less control over children's affairs and a lower capacity to monitor their educational progress. Both a change in parent–child interactions and lower involvement in children's affairs are linked to fewer inputs tailored to their children's needs, thereby lowering children's developmental opportunities. Third, parental separation leads to economic strain and discontinuities in living standards, which prevent parents from providing stable and enriched home environments under which enhancement can take place.

In sum, we expect that genetic effects on education will be weaker among adults who experienced a parental separation during childhood compared to those who grew up in stable families in the US (Hypothesis 1). However, if family structure differences are simply a reflection of socioeconomic disadvantage, we expect that genetic effects on education will not be weaker among adults who experienced a parental separation during childhood compared to those who grew up in stable families in the US once adjusted for socioeconomic circumstances during childhood (Hypothesis 2).

Few studies have acknowledged the importance of family structure for the realization of genetic influences related to educational attainment. A recent twin study concentrated on school-related skills and showed that parental separation lowered genetic influences on those skills for 10- to 12-year-olds born in the early 2000s in Germany (Baier & Van Winkle, 2021). However, as discussed above, findings from one country are not necessarily generalizable to other country context as the institutional environment across countries differ such as institutional protection against the life risk of divorce, levels of social inequality, or educational systems (see Baier et al., 2022). In addition, findings based on educationally related outcomes measured in elementary school likely differ from educational attainment achieved in early adulthood.

To our knowledge, we are the first to provide a molecular-based analysis on how family structure moderates genetic effects on educational attainment in the US based on recent PGSs for education (Lee et al., 2018) and circumvent the strong assumptions made in classical twin design. While our approach enables us to examine the potential interplay between genetic predispositions using direct measures for genetic influences and family structure, we can only identify patterns of differences in genetic influences by family structure. Thus, we cannot make any causal claims (see in greater detail in the limitations of our study supplement FAQs).

Parental separation, parental death, and genetic influences on education

In our previous discussion linking parental separation to the importance of genes for education, we concentrated on three common theoretical approaches in the literature: the family instability, parental absence, and economic disadvantage perspectives. Previous research has been unable to inch towards identifying the main mechanisms driving the moderating effects of parental separation on the relationship between genetic factors and education.

In line with previous research, we use parental death as a second comparison group to explore the driving mechanisms (e.g., Amato & Anthony, 2014; Biblarz & Gottainer, 2000; Cherlin et al., 1995; Sapharas et al., 2016). On the one hand, one might expect that the consequences of parental death are similar to children who lived with both parents because parental death is thought to be considerably more random than parental separation. For example, family instability and conflict should on average be the same across both groups, because death is not generally accompanied by conflict as is the case with separation. In addition, there is less selection into death compared to separation. Although one might suspect some health or socio-economic selection into parental death or post-death socio-economic disadvantages, these pre-death selection and post-death differences are rather small. Amato and Anthony (2014), for instance, demonstrated based on US Census data that the main reason for death among those in reproductive age, 25 and 44 year olds, is an unintended accident. Furthermore, the socio-economic consequences of parental death are less severe than for separation, because social benefits are more generous and not-means tested (see Biblarz & Gottainer, 2000). Both, spouses (up to the age of 60) and their children (up to the age of 18) are eligible for monthly survivor benefits. If the spouse continues to work, they continue to receive these benefits up to a certain threshold, while children's benefits are paid independent of the surviving parent's income and labor market status. In addition, any combined assets remain with the surviving parent and are not split in a divorce settlement.

On the other hand, one could also argue that the consequences of parental death should be more similar to the consequences of parental separation. Both separation and death result in a reduced network and a lower capacity of custodial parent to control and monitor children's activity. The comparison of parental separation with parental death enables us to explore whether a negative impact on the magnitude of genetic influences on education is rather driven by family instability, the absence of a parent, or economic disadvantage. Yet, it is likely that death and separation are each linked to unique experiences, which lowers the comparability of these two family conditions. We therefore treat the comparison with children who lost a parent as an indirect test for the proposed mechanisms. As we discuss below, we adjust all models for socio-economic conditions of the parental household during childhood in an attempt to capture selection and socio-economic differences related to family structure. Therefore, if the importance of genetic influences on education is similar among adults who experienced a parental death and those who lived with both parents, then family instability mechanisms drive the moderating effect of parental separation (Hypothesis 3a). In contrast, if the importance of genes for education is similar among adults who experienced a parental death and those who experienced a separation during childhood, then parental absence mechanisms drive the moderating effect of parental separation (Hypothesis 3b).

DATA

Study sample

We drew on data from the US Health and Retirement Study (2021) to test our hypotheses. The HRS is sponsored by the National Institute on Aging (grant number NIA U01AG009740) and is conducted by the University of Michigan. It is a cohort panel study with 16 waves of data collected biennially between 1992 and 2022. The original HRS cohort sampled in 1992 consisted of adults born 1931–1941 and their partners. In the following year, the Asset and Health Dynamics among the Oldest Old, with adults born before 1924 was added. Both cohorts were interviewed in 1998 when two additional cohorts were introduced to the study: the Children of the Great Depression born between 1924 and 1930 and the War Babies born between 1942 and 1947. Since then a sample has been added every three waves up to the most recent Late Baby

Boomer cohort born between 1960 and 1965. Response rates are generally upward of 70% and attrition rates for younger sample members tend to be relatively low with roughly 80% retention (HRS, 2023).

The analytical sample included respondents and spouses that participated in enhanced face-to-face interviews between 2006 and 2012 as well as those who completed a life history mail survey fielded in 2015 and 2017. Therefore our analytical sample was composed of members of the first six study cohorts whose main household respondent was born up to 1959. Genotyped data measuring a sample of ~2.4 million single nucleotide polymorphisms (SNP) were obtained from respondents' saliva samples collected during the enhanced interviews. Respondents were informed about the purpose and research goals and that their data is protected. Their consent was obtained through a formal process (see Ware et al., 2018 for details).

We followed the convention in the literature and restricted our genetically sensitive analyses to persons of European ancestry (see Ware et al., 2018). Thus, our results do not generalize to other ancestry groups. In the life history mail questionnaires, respondents were asked to provide information on their living circumstances before the age of 16, including information on parental separation and death. 6509 persons of European ancestry participated in enhanced face-to-face interviews as well as completed life history mail questionnaires. In addition, we were able to include an additional 170 respondents who were asked a subset of childhood family structure questions during the third wave.

Mortality bias is a potential concern for our study because childhood conditions and educational attainment are both linked to mortality (Byhoff et al., 2017; Galobardes et al., 2008). In addition, there is a correlation between genetic variants linked to education and longevity (Marioni et al., 2016). To reduce mortality bias in our sample, we excluded respondents among the oldest of the early study cohorts who may represent a particularly selective group in terms of childhood conditions, educational attainment, and genetic variants linked with educational attainment. Specifically, we excluded 2476 respondents who would have been 75 or older during the first life history survey fielded 23 years after initial data collection, which brings our gross sample to 4203. The span of 23 years is considerably shorter than life expectancy at age 50 in 1992, when the original sample cohort was fielded, which was 27 years and 32 years for White men and women, respectively (US Census, 1995).

Focus variables

We measured respondents' *educational attainment* as the number of years of schooling based on the highest degree attained (see Herd et al., 2019). In addition, we conducted analyses based on two binary outcomes as a robustness check: whether respondents acquired more than a high school education and whether respondents attained a tertiary degree. The results of these analyses were similar to those presented below and led to the same substantive conclusions.

To estimate the influences of genetic effects on educational attainment, we drew on the 2018 *educational attainment PGS* available in the HRS scientific use files (Ware et al., 2018). A PGS can be understood as a single score indicating an individual's genetic propensity for a trait. Specifically, a PGS is the weighted sum of common genetic variants or a number of reference alleles at SNPs shown to be related with educational attainment in large-scale genome-wide association studies (GWAS). The education PGS we used is based on results by the Social Science Genetic Association Consortium (SSGAC), which identified genome-wide significant SNPs at 1271 loci and accounted for 11%–13% of the variance in educational attainment in a sample of roughly 1.1 million individuals (see Lee et al., 2018). Per definition, the education PGS is standardized and normally distributed with a mean of zero and a standard deviation of one. A PGS reflects the average genetic effect of the included variants and is highly dependent on the quality

TABLE 1 Sample summary statistics by childhood family structure.

	Total	Separation	Death	Two parent
Childhood family structure		0.115	0.130	0.755
Educational attainment	14.062	13.227	13.342	14.313
Education PGS	0.024	−0.064	−0.016	0.045
Gender				
Men	0.439	0.440	0.492	0.428
Women	0.561	0.560	0.508	0.572
Birth year	1951.413	1953.026	1950.116	1951.432
Parental education	12.480	12.135	11.996	12.606
Self-rated family financial situation	2.287	2.636	2.408	2.204
Self-rated poverty	0.184	0.333	0.241	0.148
Moved due to financial difficulties	0.128	0.327	0.150	0.093
Family got financial help	0.142	0.349	0.152	0.108
Father's occupation				
Management, business, and financial operations	0.257	0.180	0.197	0.278
Professional	0.103	0.085	0.080	0.109
Sales	0.038	0.028	0.034	0.040
Office and administrative support	0.040	0.049	0.038	0.041
Farming, fishing, and forestry	0.510	0.562	0.514	0.503
Construction and extraction	0.012	0.024	0.026	0.006
Production	0.012	0.023	0.014	0.010
Observations	3754	434	511	2712

Note: Average/percentages displayed. Total includes all cases including those within missing childhood family structure information. Imputed cases otherwise not included. Data are weighted.

and sample characteristics of the underlying GWAS. We discuss the limitation of polygenic scores in the discussion as well as the supplementary file in greater detail.

Our *childhood family structure* variable was based on a number of questions in the life history mail surveys. Respondents were asked whether, before the age of 16, they lived (a) in a children's home or orphanage, (b) with a foster family or in a foster home, (c) in a boarding school, (d) whether their biological or adoptive parents ever separated or divorced, (e) or died, (f) whether one or more siblings died, (g) whether they were ever separated from their mother for longer than 6 months, (h) or their father, and (i) whether their grandparents were ever primary caregivers. In Wave 3, a subset of respondents were asked whether they continuously lived with both parents up until age 16 and if not, whether this was due to death or divorce.

Based on these responses we generated childhood family structure variable with three categories. The categories that we focused on are (1) whether a respondent experienced a parental divorce or separation, (2) a parental death, or (3) whether a respondent lived in a stable two parent family until age 16 without any instable events, that is, without any positive responses to questions (a)–(i) above. We excluded 435 cases that experienced both a parental separation and a parental death, or case that experienced any other event, that is, any positive responses to questions above except for separation, divorce and/or death, are excluded from the analyses. Our results however were robust to their inclusion. Ideally, we would have separated divorce and separation in our analyses; however, we were unable to distinguish the two events in our data (see option d above). Relatedly, we were unable to perform detailed analyses by the cause of parental death. An overview of our study sample and summary statistics of our main variables can be found in Table 1.

Analytical approach

We used OLS linear regressions to estimate how the association between the education PGS and educational attainment varies or is moderated by childhood family structure (see Figure 1). We estimated two models. First, we estimated a model including an interaction between education PGS and childhood family structure:

$$y = \beta_1 \mathrm{PGS} + \sum_{j=1}^{J} \beta_{2j} \mathrm{Family} + \sum_{j=1}^{J} \beta_3 \mathrm{PGS} \times \mathrm{Family} + X\beta^* + \varepsilon, \tag{1}$$

where years of education, y, were regressed on education PGS, family structure, and the interaction between education PGS and family structure. This allowed us to test our first hypothesis as to whether genetic effects on education were weaker among adults who experienced a parental separation during childhood compared to those who grew up in stable families. Note that $X\beta^*$ here denotes a wide range of variables whose omission might induce bias, such as parents' education, gender, birth year, and birth year-squared. As is standard in the field, we included the first 10 principle components to adjust for population stratification, that is, differences in minor allele frequencies that are attributable to ancestral differences, gender, and birth year. In addition, we used a Mill's ratio to adjust for the estimated propensity to survive until 2015, that is, the first life history survey, to account for mortality bias in our sample, as done by Domingue et al. (2017) as well as Van Winkle and Conley (2021).

We opted to estimate an interaction model, that is, a regression model including an interaction coefficient between the education PGS and family structure, because it enabled us to simultaneously quantify the difference in the average PGS coefficient across family structures and test its statistical significance. An alternative approach would have been to estimate models separately by childhood family structure and subsequently test whether the estimated education PGS coefficients significantly differed from one another. Results from such analyses were similar and led to the same substantive conclusions as those presented below.

Our second hypothesis aims at assessing whether family structure differences in genetic influences on education are simply a reflection of socioeconomic differences by family structure. Therefore, in a second model, we introduced an indicator for childhood socioeconomic status as well as interactions between the indicator and the education PGS as well as between the indicator and childhood family structure:

$$y = \beta_1 \mathrm{PGS} + \sum_{j=1}^{J} \beta_{2j} \mathrm{Family} + \sum_{j=1}^{J} \beta_3 \mathrm{PGS} \times \mathrm{Family} + \beta_4 \mathrm{SES} + \beta_5 \mathrm{PGS} \times \mathrm{SES} + \sum_{j=1}^{J} \beta_{6j} \mathrm{Family} \times \mathrm{SES} + X\beta^* + \varepsilon. \tag{2}$$

Note that the two two-way interactions were necessary to assess whether socioeconomic differences were confounding the interaction estimate between the education PGS and family structure. Rather than prioritizing just one indicator of childhood socioeconomic conditions, we opted to examine how a number of different indicators affect our results. We therefore included, in separate models, a number of relevant socioeconomic indicators prepared and harmonized in the HRS Childhood Family and Childhood Health Aggregated Data file: (1) parental education (number of years of the most educated parent), (2) self-rated family financial situation (pretty well, average, it varied, or poor), (3) self-rated poverty status (poor or not poor), (4) whether the family moved due to financial difficulties (yes or no), (5) whether the family ever received financial help (yes or no), and (6) the father's main occupation (i—management, business, and financial services; ii—professional; iii—sales; iv—office and administrative support; v—farming, fishing, and forestry; vi—construction and extraction; vii—production; or viii—transportation and material moving).

Note that with the exception of parental education, the aspects above all pertained to conditions during childhood, commonly before age 16. Parental education referred to the highest attained level of education and was collected for all parents, whether living or deceased. All childhood socioeconomic indicators except for parental education were included as categorical variables with the first category listed above as the reference. Parental education was included as a mean-centered continuous variable. Lower values on our socioeconomic indicators generally reflected less advantageous socioeconomic situations during childhood, with the exception of self-rated financial status and father's occupation, where the opposite applied. We refrained from estimating regression models that included all socioeconomic indicators simultaneously for two reasons. First, these indicators are highly correlated and would induce multicollinearity. Second, the large number of interactions that would need to be included, that is, between each socioeconomic indicator, the education PGS, and family structure, would impede the interpretability of our findings.

To account for a limited amount of missing information on our independent variables, we used chained multiple imputations and estimated coefficients and standard errors using Rubin's rule based on 20 imputed datasets (Van Buuren et al., 2006). We omitted 17 cases with missing information on our dependent variable, years of education, and 97 cases due to missing information on family structure. Our analysis sample therefore included 3754 respondents. Results acquired by listwise deletion were substantively similar to those reported below. All analyses were weighted for differential sampling probabilities and panel attrition.

RESULTS

Descriptive findings

As can be seen in the summary statistics presented in Table 1, roughly 75% of respondents grew up with two parents compared to 12% who experienced a parental separation and 13% who experienced a parental death. As would be expected, we found that respondents who lived continuously with both parents until age 16 achieved on average a higher level of education than respondents who experienced a parental separation or death during childhood. Adults from stable two-parent families had an average of 14.3 years of education, roughly 1 year more than adults in our separated and parental death sample. The education PGS was normally distributed with only negligible and non-significant deviations across groups, which indicated that there were no systematic differences among adults who grew up with two parents, adults whose parents separated, and those who lost a parent in the distribution of education PGS (see Figure 2).

As expected, we found that adults who experienced a parental separation report more disadvantaged socioeconomic conditions during childhood compared to those who grew up with both parents. Parents had an average maximum education of 12.6 years among our two-parent sample, compared to 12.1 among our separated sample. The fathers of respondents from two-parent households were also more likely to have management or professional occupations, while separated fathers were concentrated more in manual occupations. Self-

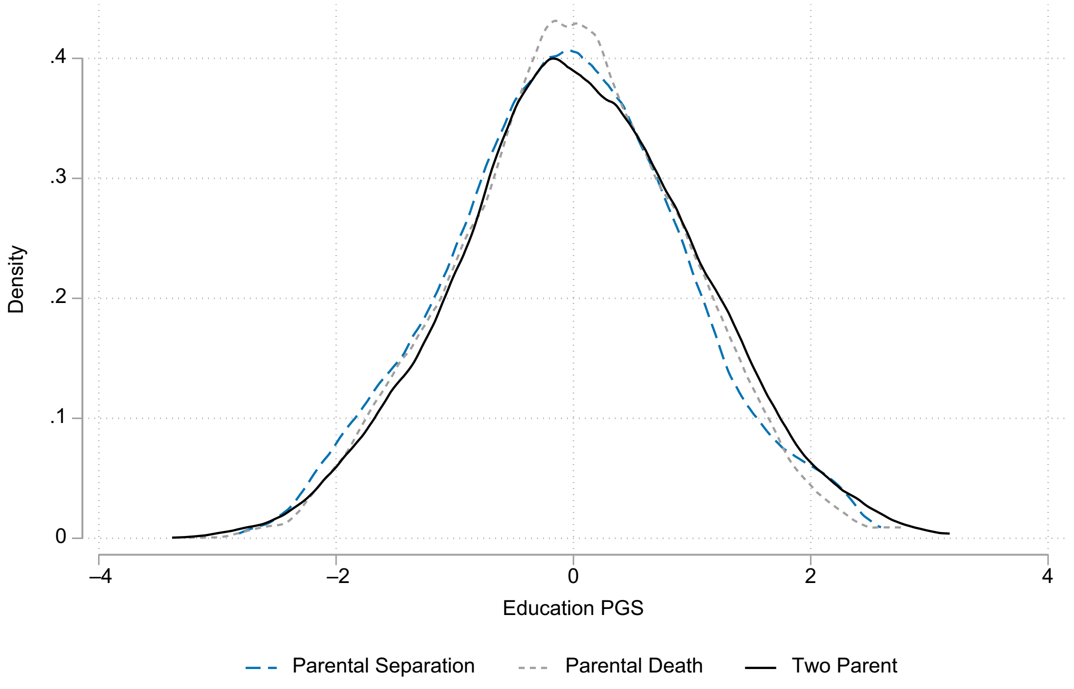

FIGURE 2 Distribution of education PGS by childhood family structure. [Color figure can be viewed at wileyonlinelibrary.com]

reported differences were even more substantial. For example, about a third of respondents in our separated sample reported being poor during childhood, moving due to financial difficulties, and receiving financial help compared to roughly 10% of respondents who lived with both parents. Adults who lost a parent during childhood tended to report socioeconomic circumstances that are less advantageous than adults who grew up with both parents but considerably more advantageous than the conditions reported by adults who experienced a parental separation.

Results from regression models

Results from OLS linear regression models of years of education on education PGS and childhood family structure are displayed in column one of Table 2. As expected, we found a positive association between the education PGS and educational attainment, which indicated that an increase in one standard deviation of the education PGS was associated with 0.61 more years of schooling for adults who lived in a household with both parents during childhood. Conversely, experiencing a parental separation or death was negatively associated with educational attainment. Compared to adults who lived with both parents until age 16, those who experienced a parental separation with an average education PGS had 0.93 and those who experienced a parental death had 0.79 fewer years of education.

In line with Hypothesis 1, we found that the importance of genes for educational attainment was lower for adults who experienced a parental separation compared to those who lived with both parents during childhood. As can be seen in Table 2, the association between the education PGS and educational attainment was roughly 0.26 lower for adults who experienced a parental separation during childhood compared to those who lived with both parents. Therefore, an

TABLE 2 Results from OLS regressions of years of education on education PGS and family structure.

	None	Parental education	Self-rated SES	Self-rated poverty	Residential move	Financial help	Father's occupation
Education PGS	0.612*** (0.05)	0.474*** (0.05)	0.639*** (0.11)	0.587*** (0.05)	0.591*** (0.05)	0.606*** (0.05)	0.473*** (0.08)
Family structure (ref. two-parent)							
Separation	−0.912*** (0.13)	−0.792*** (0.12)	−0.285 (0.46)	−0.782*** (0.15)	−0.982*** (0.15)	−0.935*** (0.16)	−0.932** (0.29)
Death	−0.813*** (0.12)	−0.700*** (0.12)	−0.772* (0.38)	−0.709*** (0.13)	−0.739*** (0.13)	−0.872*** (0.14)	−1.040*** (0.29)
Education PGS × family structure (ref. two-parent)							
Separation	−0.256* (0.12)	−0.261* (0.12)	−0.327** (0.12)	−0.286* (0.12)	−0.289* (0.12)	−0.279* (0.12)	−0.266* (0.12)
Death	−0.124 (0.12)	−0.179 (0.12)	−0.139 (0.12)	−0.116 (0.12)	−0.149 (0.12)	−0.120 (0.12)	−0.105 (0.13)
Birth year	−0.039*** (0.01)	−0.048*** (0.01)	−0.038*** (0.01)	−0.038*** (0.01)	−0.037*** (0.01)	−0.036*** (0.01)	−0.043*** (0.01)
Gender (ref. men)							
Women	−0.450*** (0.08)	−0.356*** (0.08)	−0.454*** (0.08)	−0.451*** (0.08)	−0.444*** (0.08)	−0.442*** (0.08)	−0.433*** (0.08)
Mills Ratio	−17.099*** (1.71)	−13.088*** (1.66)	−16.491*** (1.60)	−16.647*** (1.72)	−16.471*** (1.43)	−16.443*** (1.58)	−15.208*** (1.58)
Constant	95.708*** (17.54)	111.464*** (16.33)	94.823*** (16.70)	93.325*** (17.00)	92.510*** (15.44)	89.365*** (16.63)	104.220*** (16.65)
N	3754	3754	3754	3754	3754	3754	3754

Note: Unstandardized coefficients and standard errors in parentheses displayed. Main and interaction effects of socioeconomic indicators and principle components omitted. Data are weighted. Significance denoted as $+p < .10$, $^{*}p < .05$, $^{**}p < .01$, and $^{***}p < .001$.

increase in one standard deviation of the education PGS was associated with 0.35 more years of schooling for adults in our separated sample, compared with 0.61 for adults in our two-parent sample.

We found no evidence that the differential importance of genes for our parental separation and two-parent family samples was simply a reflection of socioeconomic selection or differences. Regressions with (1) parental education, (2) self-rated family financial situation, (3) self-rated poverty status, (4) whether the family moved due to financial difficulties, (5) whether the family ever received financial help, and (6) the father's main occupation showed either no or negligible change in the estimated interaction between the education PGS and family structure (see columns 2–7 in Table 2). All estimates, including the main and interaction effects of all childhood socioeconomic indicators, can be found in Table A1 (see Appendix). The estimated interaction effects and their 95% confidence intervals from those models are displayed in Figure 3 (see Figure A1 for average marginal effects). As can be seen in Figure 3, we found no support for our second hypothesis that genetic effects on education will be weaker among adults who experienced a parental separation during childhood compared to those who grew up in stable families in the US once adjusted for socioeconomic circumstances during childhood. Rather, we found that the difference in the education PGS between those who experienced a separation and those who lived with both parents was highly similar across model specifications.

Our results were impacted by the inclusion of our childhood socioeconomic indicators in only one instance. We found that one of the main effects for family structure on education attainment—but not the education PGS estimates across family structures—became statistically insignificant when self-rated childhood socioeconomic status was included in our models and interacted with both the family structure and education PGS variables. Specifically, our model indicated no statistically significant difference in the years of education between respondents

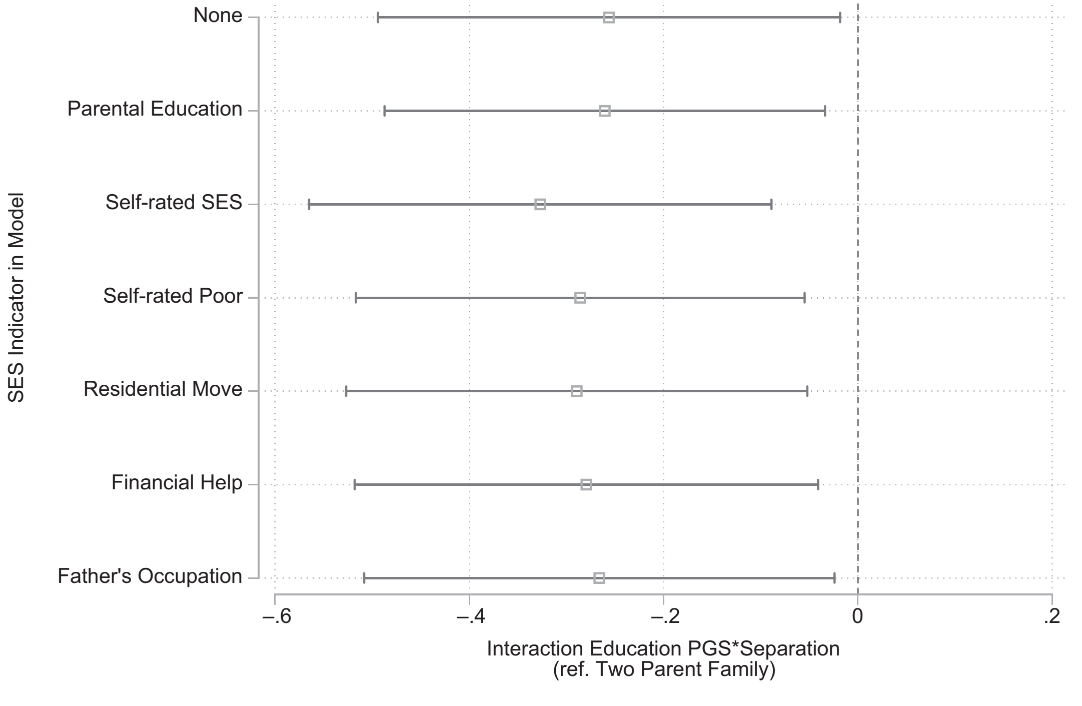

FIGURE 3 Estimated difference in the education PGS and educational attainment association for parental separation. The estimated interaction effects displayed as well as the main effects of the education PGS and family structure are reported in Table 2.

who experienced a parental separation and those who grew up with both parents but rated their socioeconomic status during childhood to be pretty well.

In contrast to parental separation, we found no statistically significant difference in the association between the education PGS and educational attainment between adults who experienced a parental death and those who grew up with both parents. Additional pairwise comparisons also demonstrated that there were no statistically significant differences in the association between the education PGS and educational attainment between adults who experienced a parental death and those who experienced a parental separation. The estimated coefficient was negative, indicating that genes tended to be less important for adults who lost compared to those who did not lose a parent. However, the estimate was relatively small in size; not even half the size of the interaction coefficient for our parental separation sample. Therefore, we found less evidence that parental absence mechanisms drove the moderating effect of parental separation (Hypothesis 3b): the importance of genes for education tended to be less similar among adults who experienced a parental death and those who experienced a separation during childhood. Rather, the importance of genetic influences on education was more similar among adults who experienced a parental death and those who lived with both parents. This indicated that the mechanism driving the moderating effect of parental separation may be more attributable to family instability than to parental absence (Hypothesis 3a).

DISCUSSION

Our study on the intergenerational consequences of parental separation on children's genetic influences on educational attainment advances our understanding of the emergence of social inequality in several ways. As sociologists become increasingly interested in the role of genetics for intergenerational transmission and children's life-course outcomes, only a few consider genetic influences empirically. Moreover, we are only at the beginning of understanding the pivotal role of the environmental conditions for the realization of genetic influences for education, which is arguably one of the most important indicators for children's life chances due to its direct link to social mobility. Previous studies have either looked at parents' social standing to acknowledge social forces on the micro-level or changes across countries or over time acknowledging socio-historical context (Baier et al., 2022; Branigan et al., 2013; Conley et al., 2015; Erola et al., 2021; Herd et al., 2019; Isunget et al., 2021; Lin, 2020; Liu, 2018; Silventoinen et al., 2020).

An important inequality-generating mechanism, however, has often been neglected in the literature: childhood family structure. Western industrial democracies have all witnessed dramatic shifts in family structure. Changes in the family context impose not only social risks for spouses but also for their children. Our integrative study—combining sociology, demography, and genetics—based on molecular data using recent education PGS (Lee et al., 2018) demonstrated that genetic factors play a smaller role for adults' educational attainment if they had experienced a parental separation during childhood compared to those who remained coupled in the US.

Our study also shed some light on the underlying mechanisms by including a number of indicators on socioeconomic conditions during childhood, but also by including parental death as a second reference group for parental separation (Amato & Anthony, 2014; Biblarz & Gottainer, 2000). We found no evidence that socioeconomic differences account for the diminished impact of genes on education among adults whose parents separated during childhood. However, we did find that the importance of genetic factors for education was more similar for those who experienced a parental death during childhood and children whose parents remained coupled compared to those who separated. This finding provides more support for the family instability perspective stating that the mechanisms run through parental conflict and psychological stress, rather than through a lack of parental control and social networks as claimed by the parental absence perspective (Cavanagh & Fomby, 2019).

It should be noted that our conclusions with regard to parental absence and family instability are indirect and inferred through a comparison with adults who experienced a parental death. This comparison may be criticized as there are distinct experiences linked to both a parental separation and the loss of a parent. Our findings suggested that there were differences in educational attainment by family structure, which may in part be attributed to differences in the average education PGSs across our family structure groups. These differences are consistent with previous research suggesting that family stress and conflict may hinder separated parents from providing enriching environments. However, in the context of our study, which investigated the intergenerational consequences of parental separation in the United States based on a genetically sensitive design including direct measures of genetic influences on education, the comparison of adults who lost a parent is one of the most suitable strategies to grasp the underlying mechanism. Given the relative similarity of adults who experienced a death and those who grew up in stable families, it seems reasonable to locate the underlying mechanism in family conflict and associated stress rather than the lack of monitoring or social networks. Nonetheless, the mechanisms need further testing, ideally with items covering adverse family dynamics. Future studies should, for instance, analyze objective measures of family conflict, such as frequency and intensity of arguments, and how this is subjectively experienced by children. Moreover, direct measures of stress, such as allostatic load, could provide valuable insights on the stress pathway. Specifically, prospectively collected data would allow us identify when during the process of separation enhancement processes are suppressed.

There are additional limitations of our study. First, recall error may bias our results as we rely on retrospective life history data. While we cannot rule out that some respondents may indeed have difficulties in remembering life events from their childhood, the question that we analyze asks broadly about whether parents separated or divorced before the age of 16. Given the severity of this family event, it seems fair to assume that they are able to provide valid information (Havari & Mazzonna, 2015). In addition, some adults may not recall aspects of childhood socioeconomic circumstances. However, the stability of our findings across six different indicators provides some positive assurance. Another age-related bias might be induced through mortality. For instance, individuals with higher education PGS also live longer and more likely to be in our sample possibly leading to an underestimation of the negative impact of parental separation. However, we implemented standard approaches to address such selection by including an indicator of survival probability in all our analyses to capture any bias induced by mortality (see Domingue et al., 2017; Van Winkle & Conley, 2021).

Despite the advanced molecular genetic methodological approach that we use in this study, it's important to acknowledge limitations of PGSs as highlighted by recent research (e.g., Howe et al., 2022; Pingault et al., 2022). First, PGSs are based on GWAS that require exceptionally large sample sizes, which are not necessarily representative. GWAS samples are mainly based on WEIRD populations (individuals from Western, Educated, Industrialized, Rich, and Democratic societies), and studies have recently even documented genetic selection into GWAS (Fatumo et al., 2022; Popejoy & Fullerton, 2016). Consequently, biases arising from non-representativeness may influence PGSs and their associations with educational outcomes (Dalton & Fletcher, 2017; Mills & Rahal, 2020).

Second, PGSs fail to encompass all genetic variants that contribute to educational outcomes. For instance, GWAS do not pick up minor genetic effects or rare genetic variants, which could cause an underestimation of the impact of genes (Pingault et al., 2022). Additionally, PGSs also capture environmental influences and thereby introduce environmental bias into the estimates (Howe et al., 2022; Lee et al., 2018). This could especially be the case when there is a long period between the collection of genetic material, the creation of the PGS, and the timing of parental separation as well as educational attainment.

Third, population stratification may bias our findings and affect the applicability of PGS to other samples. Population stratification arises from differences in allele frequencies among subpopulations due to systematic ancestry differences, potentially leading to spurious associations if not properly addressed (see the chopsticks example, e.g., Conley, 2017). While we included principal components—a standard method in genetic literature—to address population stratification, the accuracy of prediction may still be limited (Martin et al., 2019; Mostafavi et al., 2020), likely due to a mismatch between GWAS discovery samples and prediction cohorts. Additionally, prediction accuracy can vary considerably across groups having similar ancestry due to socio-demographic differences (SES, age, or gender) or basic study design differences of GWASs.

Fourth, an important limitation is the mismatch between GWAS discovery samples and prediction cohorts which can lower the accuracy and generalizability of PGS across different populations (Martin et al., 2019; Mostafavi et al., 2020). Mostafavi et al. (2020), for instance, demonstrated that PGSs derived from GWAS may not perform equally well across different populations, especially if there is poor overlap in socio-demographic characteristics of the discovery sample and the target population.

Fifth, processes related to gene–environment correlations (rGE), genetic confounding, and/or pleiotropic effects may confound our findings. Genetic influences on divorce are well-established in the literature (Salvatore et al., 2018; Van Winkle & Conley, 2021). If genetically influenced personality characteristics affect both the likelihood of parental separation as well as children's problem behavior and/or their education, then the adverse consequences of parental separation may run through shared genes and not through the environmental exposure to parental separation. Several studies have investigated to what extent rGE drives the impact of divorce (see for a review Amato, 2010). These studies used quantitative approaches rooted in behavioral genetics that disentangle genetic from environmental influences, mostly exploiting adoption or children of twin (CoT) designs. For children's internalizing and abnormal behavior, studies show that the negative impact of separation is not driven by shared genetics (O'Connor et al. 2000; D'Onofrio et al., 2005, 2006). Evidence for educational outcomes is mixed and differ by indicator (see Baier & Van Winkle, 2021). O'Connor et al. (2000), find support for rGE for children's reading competency, parental reports on children's achievement, and children's self-reported attitudes about educational achievement. In contrast, D'Onofrio et al. (2005) find no support for rGE when assessing grade repetition and years of education. Overall, previous research finds little or no evidence for rGE, and concludes that rGE does not seem to be the driving force behind the negative impact of parental separation on children's achievement. Genetic correlation refers to the genetic overlap among traits (e.g., educational attainment and the likelihood of separation). This is different from rGE which highlights how genetic influences shape environmental exposures. Genetic correlation is about the shared genetic architecture of different individual outcomes. For instance, there is a negative genetic correlation between genetics linked to educational attainment and number of children (Harden & Koellinger, 2020). Importantly, genetic correlations do not imply causal pathways as the underlying processes may be environmentally mediated (Harden & Koellinger, 2020; Wedow et al., 2018). Lastly, there might be pleiotropic effects at play, meaning that a single genetic variant influences multiple traits (Solovieff et al., 2013). For instance, genetic variants captured in the PGS for education may also influence individuals' ability to deal with family disruption. Future research therefore should analyze how specific genetic variants in the PGS for education might differentially affect various traits in children from separated versus intact families, providing a more comprehensive understanding of the gene–environment interactions at play.

In light of these complex processes underlying the gene–environment interplay, our findings on the association between parental separation and genetic influences on educational attainment may not be solely due to family structure itself. Rather, the association reflects a broader interplay of genetic and environmental factors where genetic predispositions affect both educational outcomes and family dynamics. Future research should aim to disentangle these processes by analyzing within-family designs ideally in a longitudinal setup (e.g., Howe et al., 2022). A within-family education PGS was unfortunately not available in the HRS data. Within-family designs can better account for shared environmental factors and genetic background, and hence increase the accuracy of PGSs. In addition, it is to hope that future studies use more diverse and representative samples to address issues of population stratification and cohort mismatch. Incorporating diverse populations enhances the generalizability of findings and reduces biases related to non-representativeness.

Overall, our research shifts attention to an overlooked dimension of children's disadvantage and opens up routes for further research, specifically on heterogeneous effects. First, our sample includes a number of cohorts that experienced divorce before the dissemination of the no-fault and unilateral divorce legislation by the mid-1970s (Buehler, 1995). Sensitivity analyses show that the association between the education PGS and respondents' educational attainment is not driven by cohort differences. Nonetheless, it is the hope that future research should examine whether the importance of genes for education among adults who experienced a parental separation during childhood varies across birth cohorts. For example, the increasing negative social gradient in separation and divorce, including greater economic hardship, discontinuities in living standards, and adverse psychological consequences, may have further strengthened the negative impact of both family instability and parental absence.

Second, children's vulnerabilities may be age-dependent. Developmental theories propose that early childhood is the most vulnerable phase of children's lives, as children rely almost exclusively on the resources and stimuli provided by their parents. Therefore, the negative impact of parental separation on genetic influences on education may be largest during early childhood, a period marked by increased responsiveness to environmental conditions (Cunha & Heckman, 2008).

Third, there may be differences by gender. Previous research demonstrated that daughters suffer more from the experience of parental separation than boys (Boertien & Bernardi, 2022). In addition, research for the US shows that the strength of genetic influences on education differed for men and women with cohort variation associated with changing educational opportunity structures (Branigan et al., 2013; Herd et al., 2019). Future research should therefore examine whether our findings on parental separation and children's genetic influences on education differ by child's gender.

Finally, a promising research area is to focus on circumstances where parental separation is beneficial, that is, the best solution for all. There are certainly incidences in which a breakup lowers stress levels and may even help the custodial parent create an enhancing rearing environment. Relatedly, children's relationship to the non-custodial parents should also be taken into account in further research, as a stable and good relationship may protect children as well from stress and buffer some of the adverse consequences.

Overall, our findings reveal differences in genetic effects on educational attainment in adulthood by childhood family structure. Thus, our findings indicate that distinct family conditions related to parental separation besides socioeconomic differences may reduce genetic influences on children's education, which may impact a substantial proportion of children experiencing a parental break up during childhood. While it is important to responsibly conduct genetically sensitive research and be aware of the ethical implications, integrative studies like ours—combining family demography, sociology, and genetics—are essential and needed to better understand the consequences linked to family instability.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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