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The role of gender in gene by family SES interactions – A twin study across four European countries

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ABSTRACT

Studies of gene-by-family socioeconomic status (GxSES) interactions in educational outcomes have yielded mixed findings. Building on a socio-contextual perspective, this study emphasizes that genetic influences are shaped not only by family environments but also by broader social forces, including gender and institutional context. Prior sociogenetic research, for example, suggests that early school tracking may suppress genetic influences. Using large twin registers from Finland, Norway, Germany, and the Netherlands, we analyzed gene-by-environment interactions by parental education and child gender, employing non-parametric gene–environment interaction models. Our results showed that genetic influences in Germany were weaker, and shared environmental effects were stronger, than in the other countries. We found no significant gender differences in the magnitude of genetic or environmental effects on educational attainment. Analyses of GxSES revealed that the form and strength of interactions depend on both gender and country context. In most countries, we observed a negative interaction among women, meaning that genetic influences were weaker among individuals from high-SES families. Among men, GxSES varied across contexts, appearing positive, negative, or absent. We conclude that country context and gender shape gene-by-SES interactions in educational attainment and may help explain the mixed results reported in previous GxSES studies.

1. Introduction

Stratification research has documented that higher parental socioeconomic status (SES) provides greater access to educational resources, more supportive learning environments, and various pathways to academic success (e.g., Blau and Duncan, 1967; Bourdieu and Passeron, 1990; Breen and Jonsson, 2005). This focus has extended to the interplay with genetic factors. Genetically inherited characteristics, such as cognitive and non-cognitive skills, influence educational attainment, and their effects are moderated by parental SES (Baier et al., 2022; Baier and Lang, 2019; Erola et al., 2022; Ghirardi and Bernardi, 2025; Krapohl et al., 2014).

Research on gene-environment interactions (GxE) in educational attainment and related outcomes (e.g., educational achievement, cognitive ability) yields mixed and inconclusive findings regarding the role of parental SES in moderating genetic influences (Baier

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et al., 2022; Ghirardi and Bernardi, 2025; Tucker-Drob and Bates, 2016). Some studies find that genetic influences on educational attainment are stronger among children from high-SES families, suggesting that parental SES facilitates the realization of genetic potential (Baier and Lang, 2019; Erola et al., 2022). In contrast, other studies report reversed patterns of interaction or no significant moderation by SES at all (Ghirardi and Bernardi, 2025; Tucker-Drob and Bates, 2016).

The mixed results of GxE by parental SES may reflect variations in how GxE operates in broader, more distal environments. A growing socio-contextual perspective emphasizes that genetic influences on educational outcomes are not uniform across all environments but are instead filtered, shaped, and altered by broader, more complex social contexts (Baier et al., 2022; Herd et al., 2019). From this perspective, family SES represents only one dimension of the social environment that conditions genetic effects. Broader environments, ranging from pervasive social forces (e.g., gender[1]) and institutions (e.g., educational systems), also structure opportunities for the influence of genetics (Arpawong et al., 2023; Herd et al., 2019). For instance, gender is not merely an individual trait but is embedded in structural inequalities and cultural expectations that differentially shape educational opportunities for women and men. Further, biological sex differences can be expected to influence education via genetic channels, although the differences between women and men in genes associated with education might be small (Martin et al., 2021; Reynolds et al., 2022; Ritchie et al., 2018). Indeed, a few recent studies have shown that the gene-by-SES interaction (GxSES) in education differs by gender (Arpawong et al., 2023; Stienstra and Karlson, 2023) and varies across country contexts (Baier et al., 2022; Baier and Lang, 2019). Yet empirical research rarely moves beyond the family to systematically examine how broader factors, including gender and societal-level factors, may moderate genetic influences on educational attainment.

This narrow focus is problematic for several reasons. First, genetic influences and their interactions with SES may conceal important differences between subgroups raised in distinct social environments. For instance, social experiences related to gender, such as differential educational expectations, opportunities, and constraints, may influence the degree to which genetic influences are realized. Second, research risks mischaracterizing and simplifying the understanding of genetic effects without attending to multiple relevant environments (cf. Cheesman et al., 2022). The bioecological model (Bronfenbrenner and Ceci, 1994), which underpins most of the GxSES research, highlights the importance of multiple environmental levels in shaping genetic influences and, hence, individual outcomes. However, most studies remain limited to examining only the family context. Finally, practical constraints have limited researchers' ability to examine these broader moderators, as small and selected samples make it difficult to detect variation in genetic influences across broader environments (Herd et al., 2019).

In this study, we address these gaps by moving beyond the family-level focus and examining how genetic and environmental contributions to educational attainment vary not only by parental education but also by gender and across different national contexts. We have three research questions: 1. How much do genes and environment explain the variance in educational attainment across the countries? 2. Are there differences in genetic and environmental effects between women and men in educational attainment across the countries? 3. How does GxE by parental education level differ between males and females across countries? To answer the questions, we use non-parametric gene-environment interaction models applied to large, representative twin and sibling data from multiple European countries: Finland, Norway, Germany, and the Netherlands.

Next to nuanced differences in their welfare regimes and gender norms, the most significant institutional contrast among these four countries lies in their educational structures. Specifically, Germany and the Netherlands utilize more selective systems characterized by early tracking (occurring around ages 10–12). In contrast, Finland and Norway employ more comprehensive models, delaying tracking until age 16.

Educational systems with later tracking show less educational stratification by family background (Pekkala Kerr et al., 2013). Furthermore, later tracking has been linked to stronger genetic influences, particularly among boys and men (Baier et al., 2022; Knigge et al., 2022; Lahtinen et al., 2024). It can be expected that GxE by parental education, gender, and their intersection varies across institutional contexts, underscoring the need for a socio-contextual approach that moves beyond family SES.

By considering family SES and the broader environmental factors – gender and country context – we gain a deeper understanding of how social stratification processes interact with genetic influences on educational attainment. While the four countries under study share a similar European socio-political and cultural landscape, they offer a meaningful contrast in their educational structures, which we theorize to be the primary characteristic driving country differences in our analysis. To our knowledge, there is only one country comparison with testing GxSES (Baier et al., 2022); however, it did not analyze GxSES by gender.

While this study does not allow causal inference regarding institutional effects, the results provide descriptive insights that may still inform policy debates. By clarifying how genetic and environmental influences on education differ by gender, we offer evidence on how specific educational systems relate to equality of opportunity and the underlying mechanisms of the gender gap in educational attainment (see e.g., Pekkarinen, 2008). Further, this paper may inform policymakers regarding the extent to which educational attainment is shaped by environmental factors, such as family background, which are potentially modifiable through policy intervention (e.g., Lahtinen et al., 2024). Specifically, our analysis of gene-environment interactions (GxE) helps to identify whether certain educational systems allow genetic influences on education to unfold more equitably or if social barriers suppress this potential, particularly for one gender over the other.

[1] In this paper, we conceptualize gender as a social structure while also taking biological sex differences into account. For this reason, we use both terms where appropriate. When discussing the data specifically, we use *sex*, as the dataset primarily reports sex assigned at birth.

2. Theoretical background

2.1. Gene-by-family SES interaction

Inherited genetic traits related to both cognitive and non-cognitive skills play a significant role in shaping educational outcomes (Krapohl et al., 2014). Family SES may alter the effect of genetic factors associated with educational attainment. Most studies hypothesize a *positive interaction* where genetic influences on educational outcomes are stronger in higher-SES families. In the literature, this GxE mechanism has also been referred to as enhancement (Baier et al., 2022; Shanahan and Hofer, 2005). This can be derived from the bioecological model, which proposes that genetic influence for developmental outcomes like educational attainment is realized through continuous interactions with environmental factors, known as proximal processes, operating across multiple contextual levels (Bronfenbrenner and Ceci, 1994). For instance, high-quality learning stimuli such as parental engagement and better schooling opportunities can continuously foster the expression of genetic propensities for educational success (cf. Ghirardi and Bernardi, 2025). In high-SES families, this is thought to occur more regularly and effectively. High-SES parents often hold higher educational expectations and possess sufficient resources to create a learning-stimulating home environment that is better tailored to their child's specific abilities and skills (Baier and Lang, 2019). Consequently, children raised in high-SES family environments are more likely to actualize their genetic potential, whereas those in low-SES contexts face greater constraints that may hinder their expression (Baier and Lang, 2019; Scarr-Salapatek, 1971). Also, social control can play a role in restricting the realization of genetics (Shanahan and Hofer, 2005). For example, the realization of the genetic potential of low-SES children could be constrained by lower educational expectations and high tuition fees.

Alternatively, in the case of a *negative interaction*, genetic influences are weaker in higher-SES families. The compensation mechanism (Shanahan and Hofer, 2005) and compensatory advantage model (Bernardi, 2014) propose that the adverse effects of lower genetic potential (or genetic risks) on educational attainment can be reduced or even eliminated by socioeconomically advantaged families (see also Ghirardi and Bernardi, 2025). Affluent families possess more resources to mitigate disadvantageous genetic predispositions, such as children's learning and behavioral problems. Consequently, compared to low-SES families, the genetic influence would be lower, and the family background influence would be stronger among children in high-SES families.

A negative GxE can also be expected based on the triggering mechanism (Shanahan and Hofer, 2005) and diathesis-stress model (Monroe and Simons, 1991; Rende and Plomin, 1992). Adverse genetic predispositions (such as genetic risks for learning and behavioral problems) could be activated or exacerbated by exposure to negative events or stressors in the environment. Triggering can be considered, for example, parental divorce, which is more common in low-SES than high-SES families (Baier and Van Winkle, 2021). Children from higher-SES backgrounds are typically exposed to fewer such risk factors, therefore neutralizing the influence of lower genetic propensities for educational attainment.

In the social science genetics literature, most studies have focused on identifying whether the interaction between genetic influences and family SES is positive or negative, but have been limited in their ability to examine the specific mechanisms underlying these interaction patterns. A meta-analysis of GxSES twin studies for cognitive ability and achievement tests found support for a positive interaction in U.S. studies, while in studies from Western Europe and Australia, there were no or negative interactions (Tucker-Drob and Bates, 2016). Findings for educational attainment are more limited but likewise mixed and inconclusive (Baier et al., 2022). Some twin and polygenic index (PGI) studies, the latter measuring genes at the molecular level, report a stronger genetic influence in high socioeconomic status (SES) families, for example, in Germany, Finland, Denmark, and among U.S. women (Baier and Lang, 2019; Erola et al., 2022; Ronda et al., 2022; Arpawong et al., 2023). Others find the opposite, with stronger genetic effects in low-SES families, suggesting a compensation mechanism (Lin, 2020; Ghirardi and Bernardi, 2025). Other studies report no significant interaction (Conley et al., 2015). These previous findings suggest that GxSES is not uniform across populations or contexts. In the following sections, we build on this insight by examining gender and country differences.

2.2. Gender and sex differences

We conceptualize gender as a social structure that is embodied with biological sex. Biologically, sex gives rise to two distinct physiological pathways, reflecting differences in hormonal profiles and sex-based patterns of gene expression (Rawlik et al., 2016). Throughout the life course, gender roles and societal expectations result in systematic differences in environmental exposures for men and women. A previous study found that sex-specific genetic architecture for educational attainment is small (Martin et al., 2021). However, it is not known how genetic variants across sexes respond to different stimuli, such as educational tracking (Gui, 2021).

In many contemporary societies, women now outperform men in educational achievement and attainment (DiPrete and Buchmann, 2013). While this reversal in the gender gap in average outcomes is well documented, less attention has been paid to the underlying etiology of educational attainment. That is, beyond mean-level differences, men and women may differ in the degree to which their educational outcomes are shaped by genetic and environmental factors. Understanding these differences is crucial for unpacking the broader structure of educational inequality.

One set of explanations focuses on patterns in the cognitive and non-cognitive development of females and males. Research suggests that cognitive and non-cognitive traits, which are partly heritable, are unequally distributed and expressed among men and women (Hicks et al., 2008). Boys more often have learning and behavioral difficulties (e.g., reading disabilities, antisocial behavior, ADHD) (Buchmann et al., 2008; Buchmann and DiPrete, 2006), which negatively affect later academic outcomes and are partly genetic in origin (Faraone and Larsson, 2019). Girls tend to develop socially and biologically earlier than boys, giving them an advantage in learning during childhood and adolescence (Giedd et al., 2012; Kaczkurkin et al., 2019; Lenroot et al., 2007; Ruigrok et al., 2014). It has been shown that the genetic correlation of school performance (GPA) with traits such as achievement striving and self-control is stronger for girls than for boys, suggesting that for girls these traits more effectively translate into academic success (Hicks et al., 2008). Further, genetic variants that might be associated with behavioral traits (i.e., educational attainment) show a sex-specific gene expression profile during critical developmental periods. Higher gene activity was observed in males prenatally and during puberty and in females during the first four years of life (Shi et al., 2016).

A second explanation is related to boys' greater sensitivity to the environment. Across nearly all OECD countries, boys exhibit more variability than girls in academic performance (Machin and Pekkarinen, 2008). This pattern supports a growing body of research suggesting that boys' educational outcomes are more responsive to contextual factors. Boys appear to be more strongly affected by both family and school environments than girls, with disadvantaged conditions having a particularly negative impact on boys' educational performance and later attainment (Hopcroft and Martin, 2016; Salminen and Lehti, 2023; Stienstra and Karlson, 2023). Hence, it can be expected that there is more environmental variance for men than for women. From a GxE perspective, this increased sensitivity means that men's genetic predispositions may be more readily triggered or suppressed by environmental conditions (Belsky and Pluess, 2009). Such a GxE will be captured in the genetic component if it remains unmodeled in twin analyses.

Lastly, gender differences in the etiology of educational attainment are also structured by broader societal forces. Social expectations, institutional norms, and educational environments shape the extent to which individuals can realize their genetic propensities and/or are constrained by environmental factors. For instance, Herd et al. (2019) found that the relationship between genetics and educational outcomes was weaker for women than for men. However, as opportunities changed in the 1970s and 1980s, and many middle-aged women went back to school, the relationship between genetic factors and education strengthened for women as they aged. As constraints limiting women's educational attainment declined, gender differences in the relationship between genetics and educational outcomes weakened. In twin analyses, such context-dependent realizations of genetic potential are reflected in the genetic component.

A growing body of empirical work has examined whether the genetic influences on educational attainment differ by gender. Several studies report higher heritability estimates of educational attainment for men than for women, including in the U.S. (Arpawong et al., 2023; Silventoinen et al., 2004), Norway (Ørstavik et al., 2014), and Spain after the educational policy reform of 1970 (Colodro-Conde et al., 2015). A meta-analysis by Branigan et al. (2013) similarly found that the relative contribution of genes was larger for men. However, these studies mostly report the relative importance of genetic influences (i.e. the heritability) as opposed to environmental influences by gender, and do not report the absolute variance components, obscuring the ability to conclude if differences in heritability are related to differences in genetic or environmental variance. Other studies find no gender differences in genetic effects on educational attainment, such as in Australia (Marks, 2017), Finland (Silventoinen et al., 2004), and pre-reform Spain (Colodro-Conde et al., 2015). Taken together, these mixed results illustrate the contextual nature of gender differences in the etiology of educational attainment. Importantly, in more recent cohorts, where mean educational attainment is now equal to or higher among women, differences in genetic variance components may diminish or take on new forms, reflecting shifting societal norms and opportunity structures.

A few studies are taking the next step by providing more contextual insights into gender differences in genetic influence on educational attainment (EA). There are only two studies investigating gender differences in genetic influence on education across family SES. In a study of educational achievement in Denmark, Stienstra and Karlson (2023) found that boys in high-SES families had a lower genetic component compared to boys in low-SES families, consistent with a compensation mechanism of GxSES. Such a negative GxSES was not observed for girls. Contrastingly, studying educational attainment Arpawong et al. (2023) found no GxSES for men but only for women. For women, the GxSES was non-linear, with genetic variance being smallest in middle-SES families and largest in high-SES families. However, this study was conducted on cohorts born in the early 1940s, when men had, on average, higher educational attainment than women.Some studies integrated temporal and national contexts. For example, Herd et al. (2019) found that as educational opportunities for women expanded in the U.S. over time, gender differences in the relationship between genetics and educational outcomes weakened. Branigan et al. (2013) reported no gender differences in genetic influences on EA within Scandinavian samples, suggesting that egalitarian educational systems may moderate gender differences in the expression of genetic influence.

2.3. Institutional context

Cross-national research shows that the heritability of educational attainment is not fixed but varies across countries (Branigan et al., 2013). Country differences have been linked to social mobility patterns. In countries with higher intergenerational social mobility, heritability is higher (Engzell and Tropf, 2019). The absolute variance components show that this is driven by a reduction in shared environmental factors, rather than an absolute increase in genetic variance. Also, heritability is argued to be moderated by welfare state regimes, with higher heritability in more egalitarian welfare states (Baier and Lang, 2019; Erola et al., 2022). However, Baier et al. (2022) show that genetic influences on educational achievement are strong not only in egalitarian welfare states like Norway and Sweden but also in the United States, suggesting that a more nuanced picture of the diverse institutional settings can shape genetic expression.

Educational systems in countries, particularly those involving early educational tracking, also play a role. Early tracking may hamper the expression of genetic influence and strengthen the role of the family environment (Knigge et al., 2022). Later tracking has indeed been found to be associated with a larger role of genetics (Baier et al., 2022; Knigge et al., 2022; Lahtinen et al., 2024; but for a null result, see Mönkediek, 2022). Lower tracking and less stratified systems have been linked to higher educational equality because successful navigation through the system is less dependent on parental input (Breen and Jonsson, 2005).

Apart from educational tracking, two additional features of national education systems have been shown to influence equality of educational opportunity in studies that are not genetically informed: the cost of education and enrolment rates. Lower financial constraints on educational attainment have been shown to narrow educational differences between children of different backgrounds (Birkelund, 2006). Higher enrolment rates support educational opportunities because educational attainment is less selective.

The institutional context may also shape gender differences in the genetic component of educational attainment, depending on the gender norms, labor market opportunities, and institutional constraints present in a given country. In more gender-equal societies, where structural barriers for women's education and careers are lower, genetic influences on educational attainment tend to be more similar between men and women (Branigan et al., 2013; Marks, 2017). Indeed, studies have shown that in more recent cohorts, when women's educational opportunities expanded, the differences between men's and women's genetic effects have been narrowed or even faded away (Baker et al., 1996; Herd et al., 2019; Lahtinen et al., 2024). Studies without genetically informed designs have found that the gender gap is dependent on the educational system, with later tracking benefiting girls (Hadjar and Buchmann, 2016; Pekkarinen, 2008; Scheeren et al., 2018). Combined with the indications from genetically informed designs that show that the timing of tracking influences boys' genetic effect but not girls – it can be expected that the role of genetics in educational attainment differs by sex.

The observed discrepancy between studies that incorporate genetic data and those that do not likely reflects a distinction between mean-level shifts (studies without genetically informed designs) and variance decomposition (in genetically informed studies). Studies without genetically informed designs focus on mean differences, finding that girls often exhibit higher *average* educational attainment across various tracking systems. This female advantage is frequently attributed to higher levels of non-cognitive skills and stronger behavioral alignment with institutional expectations, which may buffer females against varying genetic effects by educational tracking. Therefore, although girls can benefit from delayed tracking in terms of higher educational attainment, meaning that their *average* educational attainment increases compared to boys, their (genetic) variance may not change. In contrast, previous studies have shown that delayed tracking increases variance for boys and lower performing students, which has been linked to genetic factors (Knigge et al., 2022; Lahtinen et al., 2024).

Lastly, the national context may shape how genes and SES interact differently for men and women. For instance, in egalitarian systems with universal access to education and less family-level constraint, gene-by-SES interactions may be weaker or more similar across genders. While there are, to our knowledge, no prior studies investigating this specific interplay, there are single-country studies that suggest that features of the educational system moderate the role of genetics in education in an intersectional way. For example, Lahtinen et al. (2024) analyzed Finnish school reform when Finland shifted from an early (age 10) to a late (age 16) tracking system using a PGI for education. They found that the school reform increased the genetic component of males and individuals from low-SES families, but not females and children from higher-educated families. They showed that the effect of genes on educational attainment was similar for males and females when universal curriculum reforms were implemented; however, before the reform, the genetic effect was lower for males.

2.4. Comparative study design and hypothesis of the study

We analyze GxE by parental education and gender in four European countries: Finland, Norway, the Netherlands, and Germany, using birth cohorts 1980-1998. A cross-national comparison of the analyzed country profiles is important to acknowledge to understand how GxE interactions vary under different social and educational environments. It is particularly important to understand how much countries' educational systems, labor market policies, and gender equality differ in promoting educational opportunities (Scheeren et al., 2018; van Hek et al., 2016). We acknowledge that in our four-country comparison, institutional arguments regarding the educational systems, gender, and the welfare state are operationalized through country-level labels. While this approach allows us to evaluate the consistency of our findings with existing macro-theoretical frameworks, it does not permit a formal decomposition of which specific institutional feature drives the observed variance. Consequently, our interpretations rely on theoretical inferences drawn from the comparative results rather than direct quantitative modeling of institutional variables.

2.4.1. Educational system

Germany has an early tracking system, which sorts children after primary education at the age of 10–12 (depending on the federal state). The Dutch system implements tracking after primary school to three secondary education streams at age 12. In Nordic countries, Finland and Norway, tracking is absent from compulsory schooling. In all countries, compulsory and secondary school is state-funded. Higher education is tuition-free in Finland and Norway. In Germany, there can be some nominal tuition fees. In the Netherlands, there are moderate tuition fees in higher education (see Appendix B for detailed descriptions of education systems).

2.4.2. Welfare state models

In countries with strong social safety nets and equal access to education, genetic influence may be more equally realized across SES groups. In contrast, in more unequal societies, SES may play a stronger role in determining educational outcomes (Branigan et al., 2013). The analyzed countries in this study do not drastically differ in their social welfare, although Finland and Norway's welfare support may be higher than Germany's and the Netherlands. However, macro-sociological literature typically distinguishes between three welfare regimes (Esping-Andersen, 1990, 2014): the liberal (minimal state intervention), the social-democratic (high redistribution and universal access), and the conservative (protection tied to employment and contributions). Within this framework, Finland and Norway are classified as social-democratic regimes, while Germany is categorized as conservative. Although the Netherlands is often grouped with conservative regimes, it is frequently regarded as a 'hybrid' model that shares characteristics with the social-democratic type (Arts and Gelissen, 2002).

World Bank international mobility data for the cohorts born in the 1980s show that there are no large differences in the parent-child correlation in education (see Table 1). However, previous country comparisons about the studied about the birth cohorts born in 1980s have shown that sibling correlations are highest in Germany (0.51) followed by Norway (0.41), the Netherlands (0.4), and Finland (0.37) (Grätz et al., 2021; Monden, 2010), indicating that the effect of family background is more pronounced in Germany than in other countries.

2.4.3. Gender equality

Studies have shown that the gender gap in educational attainment is related to women's higher labor market participation and society's gender ideological climate (van Hek et al., 2016). Also, in countries analyzed in this study, women's higher educational rates are higher than men's (see Table 1). Women's labor force participation rates are fairly similar, although in Finland and Germany lower than in Norway and the Netherlands. In the Netherlands, part-time employment among women is more common than in other countries; in Finland, women's part-time jobs are least common. Although Nordic countries' gender role attitudes are considered to be equal, studies show that also in the Netherlands and Germany, gender role attitudes are close to the levels of the Nordic countries (Cascella et al., 2024). According to the OECD's gender equality report, the discrimination in social institutions score (SIGI score) of all the studied countries is very low (OECD, 2023).

2.4.4. Hypotheses

Since the most striking difference between the countries lies in their educational systems, we expect this to be the primary driver of cross-national variation in the genetic contribution to educational attainment and its interaction with gender and socioeconomic status. Education systems in the Netherlands and Germany are more unequal due to early educational tracking, selective access to higher education (Germany only), and tuition fees than in Finland and Norway (see Table 1). Therefore, in these countries, parental involvement in children's educational choices may be more decisive as navigating these systems demands more parental resources, reflected in larger shared environmental effects and stronger GxSES interactions. In educational systems with later tracking, like in Finland and Norway, the cognitive demands of advanced studies can increase the impact of differences in individual learning abilities. Hence, we hypothesize:

The contribution of genetics is smaller and shared environmental effects are stronger in the Netherlands and Germany compared to Finland and Norway (Hypothesis 1).

The GxSES is expected to be stronger in the Netherlands and Germany than in Finland and Norway (Hypothesis 2).

Based on the previous gene-environment studies, it can be assumed that gender/sex differences in the genetic component of educational attainment depend on the country context. Since boys, on average, realize their cognitive and non-cognitive genetic potential later than girls and are more sensitive to the environment, they may be less likely to translate skills into future academic success if tracking occurs early. Consequently, environmental factors, such as family background, play a more prominent role in boys' educational choices. Thus, in early tracking systems, genetic effects are expected to be weaker for boys than for girls. In late-tracking systems, we do not expect to find gender differences in the effects of genes and the environment on education.

Therefore, *the contribution of genetics is smaller, and the shared environment is larger for men than women in the Netherlands and Germany, but there are no gender differences in Finland and Norway (Hypothesis 3).*

Because men are argued to be more sensitive to environmental factors than women, it can be expected that men's educational attainment is more influenced by parental involvement and disadvantaged family events than women's. Therefore, a gender difference in the GxSES can be expected, where the GxSES would be stronger for men. This can be especially pronounced in countries with an unequal education system. We expect that both institutional context and gender modify the effect of GxSES.

Gender moderates on GxSES interaction in the Netherlands and Germany, but not in Finland and Norway (Hypothesis 4).

Table 1
Country profiles of the different educational indicators.

	Finland	Norway	Netherlands	Germany
IGC	0,31	0,33	0,33	0,31
Sibling correlations	0,37	0.41	0.4	0.51
Social welfare	Yes	Yes	Yes	Yes
School tracking age	16	16	12	10-12
Higher educated % of men	36,8	41,7	47,5	33,4
Higher educated % women	52,9	60,4	56,9	36,5
Tuition fee in higher education	No	No	Yes	Small
Female labor force participation rate (%)	56	62	61	55
Female part-time jobs rate (%)	16,9	36,6	57,7	27,6
OECD's SIGI gender index score	12,1	6,7	9,5	12,4

IGC = Intergenerational educational mobility (parent-child correlation in years of education), source: World Bank database.
Sibling correlations: sibling intra-class correlation in education attainment source: Grätz et al. (2021); Monden (2010).
Social welfare: Whether countries provide social benefits and protection (Source: Llena-Nozal et al., 2022.
Higher education %: Percent of the higher educated in the population aged 25-35 in the year 2020. Source: (OECD, 2025): OECD data archive 2025, SIGI score (OECD, 2023), Incidence of part-time employment, female age 15 – 65. Source OECD, 2025).

3. Data and methods

We analyzed twin and sibling data from four different countries: Finland, Norway, the Netherlands, and Germany. We focus on birth cohorts 1985 to 1995/1997-1998, selecting the largest possible overlap across countries to ensure comparability between datasets.

In Finland and the Netherlands, data were collected from the full-population registries on all same-sex twins and siblings born between 1985 and 1995, along with their parents. The sibling data was then limited to pairs with an age difference of no more than 3 years. Overall, the data for Finland include 58,386 same-sex twin and sibling pairs (116,772 individuals), while the Netherlands' data cover 135,951 twin and sibling pairs (271,902 individuals). In both countries, the zygosity of the twins is unknown. Therefore, we used a twin method that compares same-sex twins and siblings (see Methods section). Even though zygosity information is missing for these countries, the full population dataset has advantages, such as avoiding self-selection or reporting bias.

In Norway, we used a register-based data set where zygosity is known. The data consists of linked information from both administrative registers and the Norwegian Twin Register (NTR). The NTR, established in 2009 by the Norwegian Institute of Public Health, is a large-scale, high-quality twin registry (Harris et al., 2006; Nilsen et al., 2013; 2016). Twins gave informed consent to be included in the register, signing a consent form. Due to higher participation of female twins in the NTR, the Norwegian sample shows a gender imbalance favoring females. Zygosity was validated by using DNA. Our analytical twin sample for Norway includes twins who were born between 1980 and 1995. In total, the Norwegian twin registries include 1979 twin pairs and 3958 individuals.

In Germany, Twinlife survey data were used that included information on same-sex monozygotic and dizygotic twins. TwinLife is the first twin (family) study in Germany, realizing a population register-based sampling design (Mönkediek et al., 2019). The sample covers the full distributions of core socioeconomic indicators, facilitating social stratified analyses (Lang et al., 2020). TwinLife's sampling design includes all parts of Germany (Lang and Kottwitz, 2020). It allows for reliable comparisons with twin data from other countries. From the Twinlife survey, twins aged 21 or older, born in 1990-1993 and 1997-1998, were included in this study. We used all the waves until wave 5, which was collected in 2023. In total, the German sample includes 1526 twin pairs and 3064 individuals (younger cohort: 1,140, older cohort: 1924). TwinLife researchers determined the twins' zygosity primarily through physical similarity questionnaires for parents or twins, validated by DNA samples that were collected from a subset of 328 twin pairs. The questionnaire-based zygosity classification was accurate in over 95% of the cases.

3.1. Variables

The dependent variable in each country is educational attainment in years. This was measured in Finland, the Netherlands and Norway by taking the highest education level achieved when individuals were aged 27-28. In Germany, we measured the highest level of education when twins were 21 or older.[2] In the datasets of Germany, Finland, and the Netherlands, education variables were measured according to OECD's ISCED1997 classification and then converted into years of education ranging from 7 years (elementary school) to 17 years (university degree/PhD). In Norwegian registers, education information was registered on the NUS2000 scale (Norwegian Standard Classification of Education), which was converted to years of education, similarly to other countries. The NUS2000 scale is very similar to the ISCED1997 scale. The years of education, a continuous variable, were used instead of a categorical variable due to the requirements of the complex twin modeling technique.

We measure family SES by parental education, as it has been shown to reliably reflect socioeconomic background (Erola et al., 2022). It was measured in Finland, the Netherlands and Norway at the age of 10-15. In Germany, we used the first available parental education value across the Twinlife waves. We took the information on the parent with the highest educational level. Parental education was classified into two categories: low and high. Low education indicates that parents have not attained higher education (ISCED 4 or lower). High parental education signifies that parents have reached at least the college/bachelor level (ISCED 5 or higher). We categorized parental education into these two groups to enhance statistical power.

Children's sex was included as a dummy variable in the models. Table 2 reports the summary statistics of the variables. Table 3 reports averages and standard deviations of education in years by gender in the studied countries.

3.2. Methods

To analyze the genetic and environmental contributions to educational outcomes in different countries, the classical twin design (CTD) was applied to estimate the genetic, shared, and unique environmental components. Further, to analyze GxE by parental education and sex, we used non-parametric gene-environment interactions (Stienstra and Karlson, 2023). The classical twin method is also known as ACE modeling, which utilizes the genetic similarity of the twins. While dizygotic (DZ) twins share, on average, 50% of their segregating genes, monozygotic (MZ) twins share 100% of their DNA and are genetically identical.

We used this information to decompose the total variance of an outcome into a variance component associated with (*A*), an additive genetic component that reflects genetic influences; (*C*), a shared environmental component that includes all environmental influences that make twins similar, such as influences of parental involvement and the broader environmental context, for example, neighborhoods or schools; and (*E*), a unique environmental component that captures all the influences that make twins different. The E

[2] In TwinLife data 4,9 % of the twins was still enrolled in the school we conducted the analyses without those twins, but the results remained the same.

Table 2
Summary statistics across the countries and assortative mating (correlation between parents' education).

Country	Finland	Norway	The Netherlands	Germany
Education in years	12,73	16,3	15,47	13,98
Female	0,48	0,68	0,48	0,58
Parental education high	0,23	0,53	0,35	0,60
Birth cohort	1985-1995	1980-1995	1985-1995	1990-1993, 1997-1998
Zygosity information	No	Yes	No	Yes
Assortative mating	0,43	0,49	0,44	0,42
N	152,350	3958	271,902	3052

Table 3
Averages and standard deviations of education in years and by gender within the countries.

	Finland		Norway		The Netherlands		Germany	
	Male	Female	Male	Female	Male	Female	Male	Female
Mean of education in years	12,3	13,2	16,4	16	13,2	13,8	13,7	14,2
SD of education in years	2,4	2,5	2,6	3,0	2,3	2,1	2,4	2,4

component also includes the error term, which can be expected to be smaller in the large registers than in the surveys. Because MZ twins share all their genes and DZ twins, on average, share half of their segregating genes, the covariance for MZ twins is $a^2 + c^2$, and that for DZ twins is $0.5 * a^2 + c^2$.

To estimate baseline ACE components, univariate decomposition methods were computed for each of the countries separately. ACE components are estimated by using multilevel structural equation modeling (Bates et al., 2019). The ACE univariate model formula can be written as follows:

$$V_y = a^2 + c^2 + e^2$$

where V_y is the total variance of the outcome variable and the a^2, c^2, e^2 variance components are the variances calculated from the path coefficients of the latent factors on the outcome variable. To calculate the share of the total variance of A, C, and E, each component is divided by the total variance, for example, the proportion of variance due to genes. A component can be calculated with the following formula : $A = \frac{a^2}{a^2+c^2+e^2}$

Because the register data in Finland and the Netherlands do not include information on twins' zygosity, we followed previous research and relied on the sex-composition of twins to approximate zygosity (Erola et al., 2022; Baier et al., 2022; Stienstra et al., 2024). Specifically, to enable studying gender differences, we compared same-sex twins to same-sex non-twin siblings (Stienstra and Karlson, 2023). Same-sex non-twin siblings share on average 50 % of their segregating genes, while same-sex twins can be either monozygotic, sharing 100 %, or dizygotic, sharing 50 % of their segregating genes. Relying on the assumption that same-sex (ss) and opposite-sex (os) twins are equally alike among dizygotic twins (i.e., the Weinberg differential rule), we calculated the genetic correlation between ss twins using the following formula: $(ss - os)/ss + 0.5 * os/ss$ (Fellman and Eriksson, 2006). Applying this correction yields a genetic similarity of 0.76 for ss twins in the Finnish dataset and 0.74 in the Netherlands. The genetic similarity did not differ by parental education in either country. Thus, in our identification strategy for the ACE components in Finland, the covariance for ss twins is $0.76\ a^2 + c^2$ and in the Netherlands, the covariance for ss twins is $0.74a^2 + c^2$, and for non-twin siblings is $0.5\ a^2 + c^2$. Previous comparisons suggest that twin models with unknown zygosity provide ACE components that are comparable to those acquired using information on the zygosity (de Zeeuw and Boomsma, 2017). The shared environment is assumed to be the same between twins and between siblings, while the non-shared environment is uncorrelated between twins and between siblings, as it only contributes to within-pair differences. Because the shared environment is assumed to be the same, we analyze only non-twin siblings whose maximum age difference is three years. As a robustness check, we also performed the analyses with a maximum two-year age difference between non-twin siblings. This did not lead to different conclusions, although some of the standard errors increased due to lower statistical power (see Appendix C).

We calculate covariances and derive variance components for various subgroups, employing non-parametric gene-environment interaction analyses (Stienstra and Karlson, 2023). These subgroups are defined by parental education (low vs. high) and gender (males vs. females), and their intersections. Educational attainment means and variances were constrained to be identical between twins and siblings but were allowed to vary across the subgroups of family SES and gender. In the figures, the y-axis represents the percentage of variance attributable to each component (A, C, and E), while the x-axis divides the sample into groups (sex and parental education level). The error bars indicate 95 % confidence intervals in the estimated A, C, and E components.

We report standardized variance components (relative contributions) for each country, allowing us to compare results across countries. Unstandardized variances of ACE components are reported in Appendix Tables A1-A3 and Table 3 for country comparison. We report absolute unstandardized variances because they provide complementary information about cross-country differences in total variability, and to maximize transparency and facilitate future replication of the results. Furthermore, unstandardized variances are reported in interaction models because relative variances may change because of changes in any of the A, C, and E components. In addition, reporting unstandardized variances helps to distinguish whether differences across contexts reflect changes in the overall magnitude of genetic and environmental influences or merely shifts in their relative proportions.

4. Results

4.1. *The effect of genes and environment across the countries*

According to the results reported in Table 4, the highest genetic component (A) is in Finland, followed by the Netherlands, Norway, and Germany. The highest shared environmental component (C) is in Germany, followed by Norway, the Netherlands, and Finland. Unique environmental (E) influences are fairly similar across countries, with Germany having the highest, followed by the Netherlands, Norway, and Finland.

The results partly align with our Hypothesis 1, which states that in countries with less selective, more equal education systems that promote individual later educational choices, a family or shared environment is less influential. The high proportion of the C component is surprising for Norway, as both Finland and Norway have educational systems that seem equal compared to Germany. However, a previous study also found higher C in Norway than in Sweden (Baier et al., 2022). Nevertheless, the estimated results for Norway show a fairly large error term (7.26), which introduces greater uncertainty than in other countries, and the contribution of the shared environment is not statistically significantly different from Finland (Wald test = 2.65, p = 0.10).

Fig. 1 shows the results of GxSES across the countries. We expected that a GxSES would be stronger in the Netherlands and Germany than in Finland and Norway (hypothesis 2). We find only a statistically significant negative interaction in Finland, indicating a compensation effect (see p-values in Appendix table A1). In other countries, we do not find a statistically significant interaction in the genetic component with parental education in any of the countries. Therefore, our results do not support hypothesis 2. However, in the Netherlands, there is a positive interaction of the shared environmental component being higher among the children of lower-educated parents.

4.2. *The effect of genes and environment by gender across the countries*

Next, we study whether there are differences in genetic and environmental effects between men and women in educational attainment across the countries. We hypothesized that the contribution of genetics is smaller and the shared environment is higher for men than women in the Netherlands and Germany, but there are no gender differences in Finland and Norway. Fig. 2 displays the results of the four countries by gender. It shows that there are no statistically significant gender differences in the standardized genetic, shared, or unique components in any country. Additionally, we do not find statistically significant differences in the unstandardized components (see Table A2 in Appendix A). Our third hypothesis was not supported, as gender does not seem to be a dividing factor of genetic effects on educational attainment in the studied countries and cohorts. This is in line with some of the previous studies (Marks, 2017; Silventoinen et al., 2004).

4.3. *GxSES for males and females across the countries*

We expected gender differences in the GxSES in the Netherlands and Germany, but not in Finland and Norway. Panels A-D in Fig. 3 illustrate the ACE decompositions stratified by parental education (low and high) and gender across the countries.

Panel A shows that in Finland, for both men and women, there is a statistically significant negative interaction by parental

Table 4
Relative and absolute variances were calculated by using univariate ACE sibling and twin models in Finland, Norway, the Netherlands, and Germany.

	Finland	Norway	Netherlands	Germany
A %	67,6	46,2	53,1	35,8
	4,22	*8,02*	*4,62*	*6,28*
C %	8,7	20,8	12,9	27,3
	2,23	*7,26*	*2,42*	*5,29*
E %	23,7	33,0	34,0	36,9
	2,04	*2,04*	*2,23*	*2,4*
A var.	4,06	3,46	2,57	2,1
	0,25	0,61	*0,22*	0,369
C var.	0,52	1,65	0,62	1,6
	0,13	0,55	*0,12*	0,321
E var.	1,42	2,51	1,64	2,16
	0,12	0,16	*0,11*	0,134
Total var.	6	7,62	4,83	5,86
Intercept	12,73	16,3	15,47	13,98
N	116,772	3958	271,902	3052

Standard errors in italics, second row.

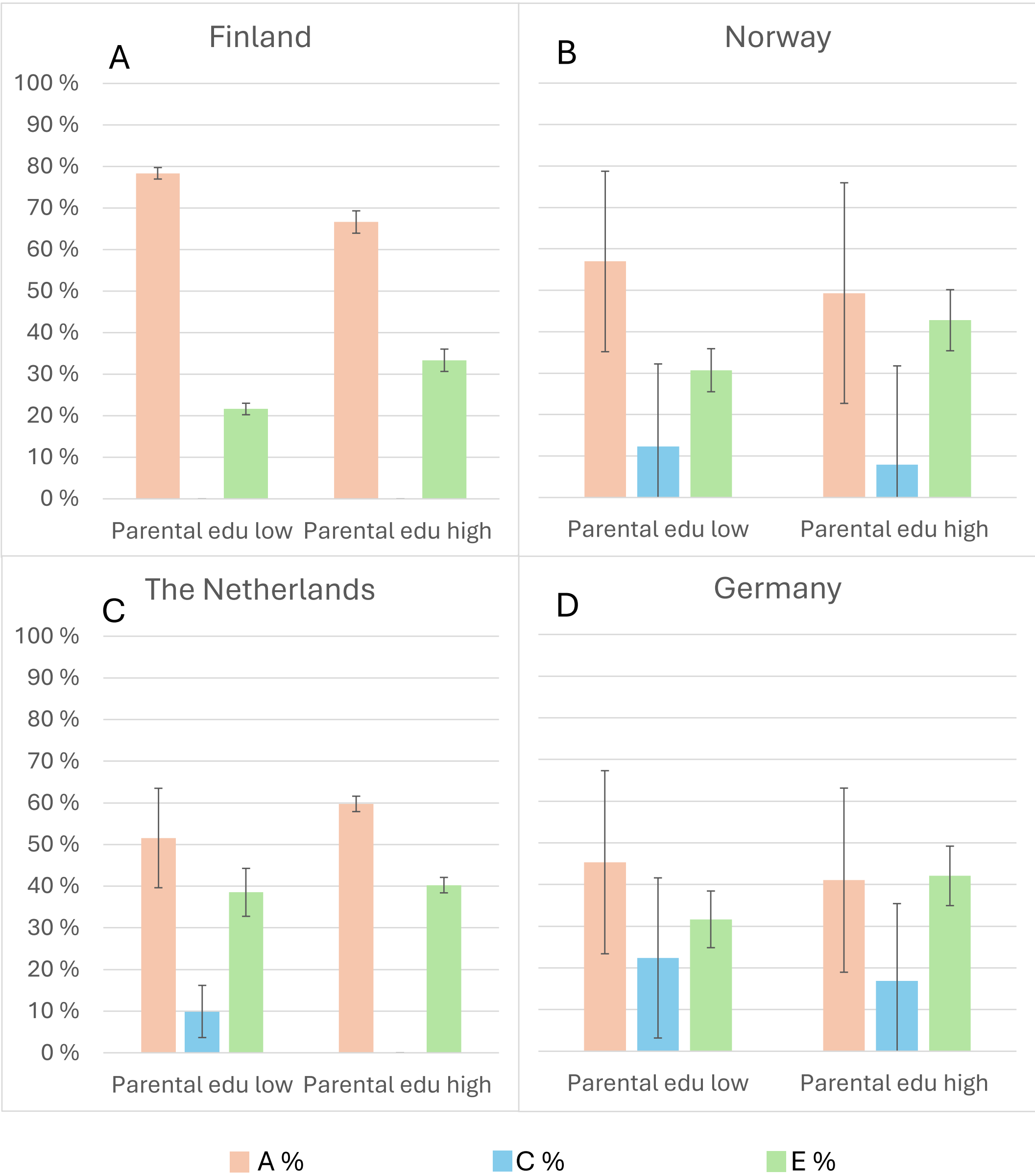

Fig. 1. Non-parametric interaction ACE-models by parental education.

education (see p-values in Appendix table A3A). The genetic component was strongest among women of the low parental education group, explaining 76.7% of the variance, compared to the high education group, 60.6%. For men with low parental education, genetic components explained 73.6% of the variance, and for men with high parental education, 65.6%. Shared environments did not contribute to the variance. However, the unstandardized results show a different pattern for men and women. For women, we observed the same negative interaction, but for men, the non-standardized results showed that the A component is larger among children of highly educated parents. This result appears because the total variance is larger among men with high compared to low parental education (see Appendix table A3A).

In Norway (Panel B), for men, we find no statistically significant GxSES (Appendix table A3B). Although there is a difference in the genetic contribution, where genetics accounted for 47.9% of the total variance for men with low parental education, compared to 63.6% for men with high parental education, the difference is not statistically significant. The parental education differences in the C and E components were not significant either. Among women, the (absolute) contribution of genetic variance is statistically significantly different between low and high-educated parents ($p = 0.012$). Also, the contribution of the unique component is significantly greater for women with high parental education than low parental education ($p = 0.008$) but the shared environment component is insignificant. Although large confidence intervals, we find evidence for negative (compensation) GxSES for women in absolute terms

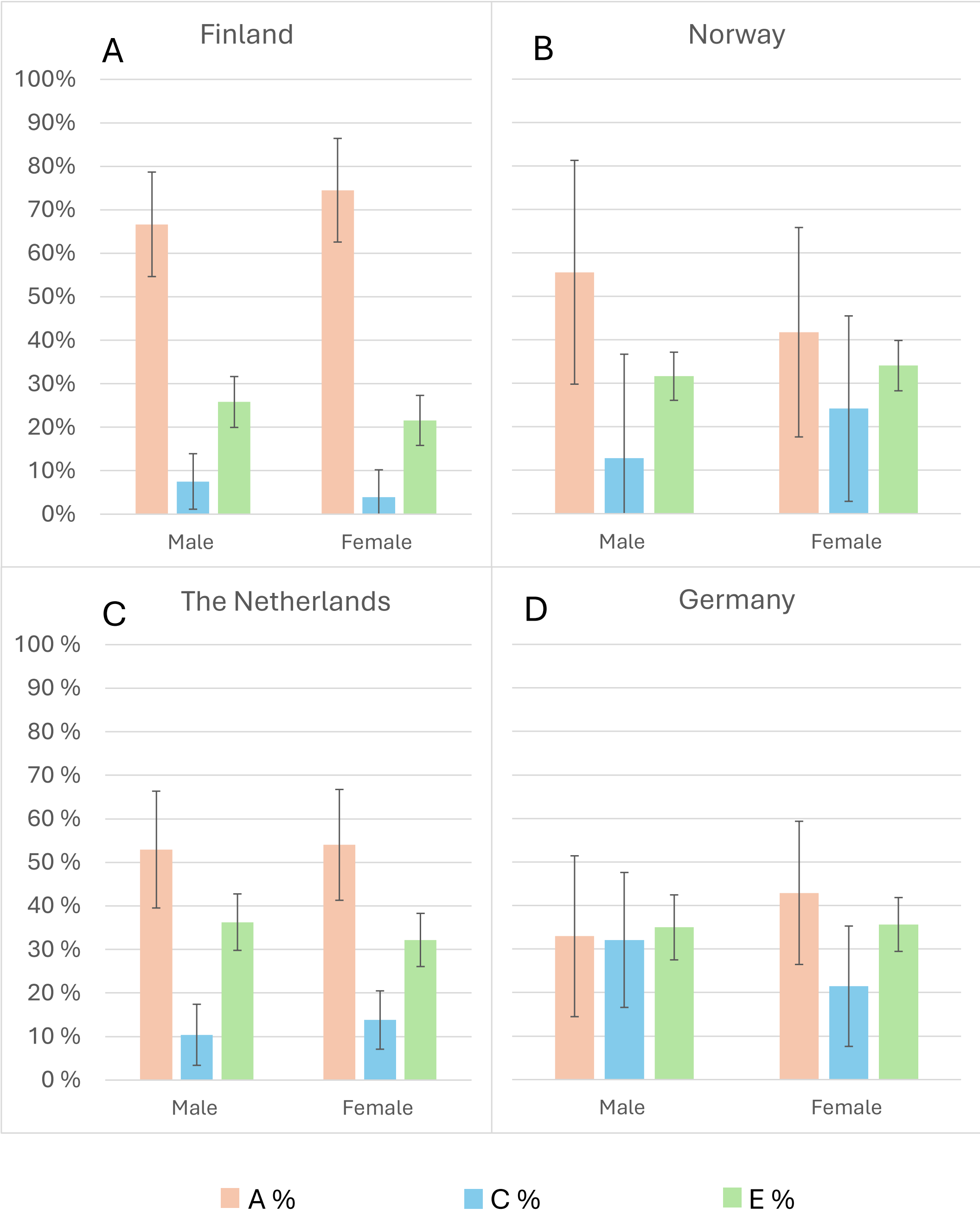

Fig. 2. Non-parametric interaction ACE-models for males and females across the countries.

(see Appendix table A3B).

In the Netherlands, we did not observe differences between parental educational groups among men or women, as displayed in Panel C (Appendix table A3C). For both men and women, the genetic contribution to educational attainment differences was slightly higher and the shared environmental contribution slightly lower if parents were highly educated. However, these differences were not statistically significant (nor were the differences in absolute variance components, see Table A3C in Appendix A). Therefore, there is no evidence for a GxE for either men or women.

Finally, panel D shows the results for the German sample. It shows a stronger genetic contribution of the total variance among men with higher-educated parents (48%) than for those with low-educated parents (19%). However, the difference is statistically insignificant (see Appendix table A3D). The shared environment contribution is statistically significantly greater ($p = 0.048$) among men with lower-educated parents (46.5 %) compared to higher-educated parents (11.2%). For women, the genetic component is higher in

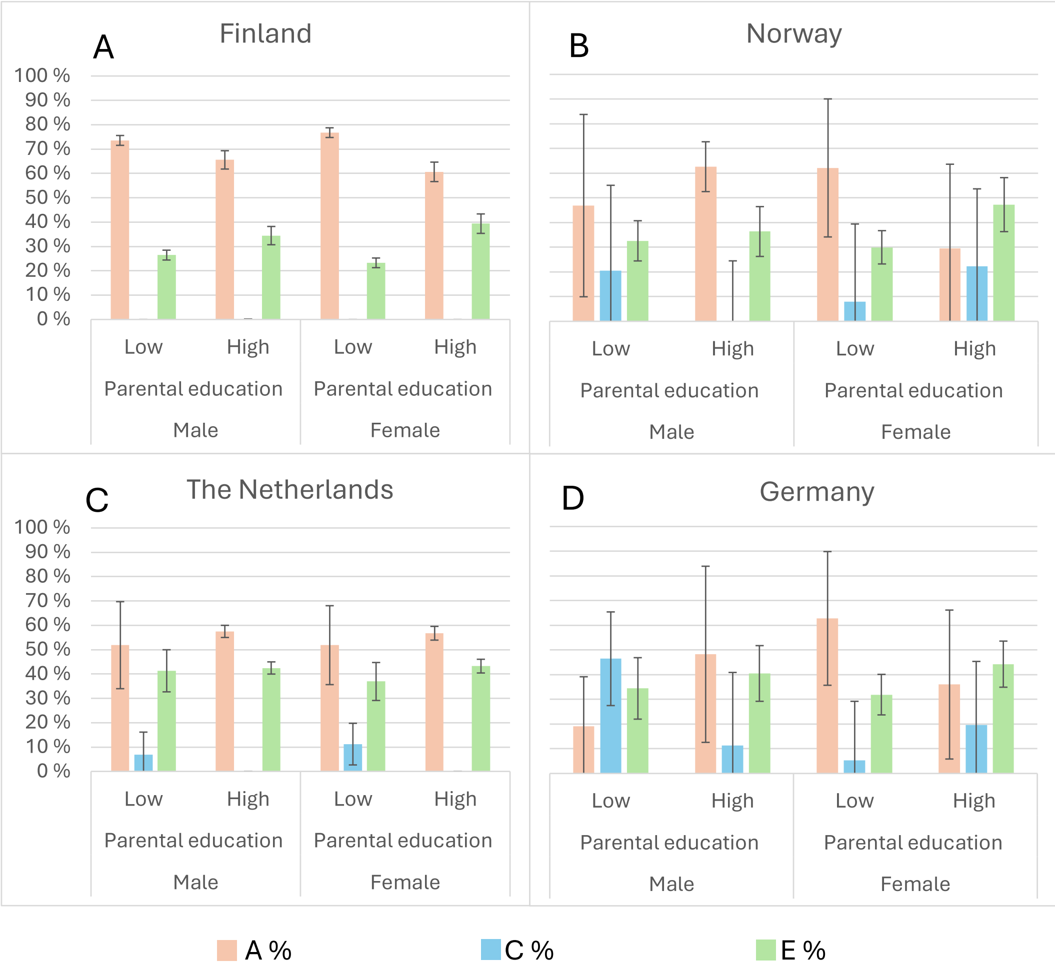

Fig. 3. Non-parametric interaction ACE-models for males and females by parental education across the countries.

the low parental education group (62.8%) compared to the high parental education group (36%), the unstandardized estimate is marginally significant ($p = 0.08$). Shared environmental influence is stronger in the high parental education group (19.7%) than in the low parental education group (5.3%), but this difference is not statistically significant. The unique environmental component is significantly ($p = 0.043$) greater in the high parental education group (44.3%) compared to the low parental education group (31.9%). The unstandardized results show that this negative GxSES is driven by a large variance in the C component and lower variance in the A component (see Appendix table A3D). Altogether, there is suggestive evidence of negative (compensation) GxE by parental education for women but not for men.

Overall, we do not find support for our fourth hypothesis, stating gender differences in GxSES in the Netherlands and Germany, and no gender differences in Finland and Norway. However, we did find negative GxSES for women in Finland, Norway, and Germany. In the Netherlands, we observe no gender differences in GxSES. While we expected that the GxSES would have been stronger for men in Germany, we find differences in the direction of the interaction instead of the strength. A similar pattern was also observed in Norway. The pattern indicated a greater genetic contribution and a lower shared environmental contribution among children of higher parental education compared to those of lower education. However, confidence intervals overlapped.

5. Conclusion and discussion

We studied the gene-environment interplay (GxE) by parental education and children's gender in educational attainment across four countries: Finland, Norway, the Netherlands, and Germany, among cohorts born in the 1980s and 1990s. Using non-parametric gene-environment interaction models, we analyzed twin and sibling data to understand how genetic and environmental factors contribute to educational attainment. Our three research questions were: how much do genes and environment explain the variance in educational attainment in the studied countries? Are there differences in genetic and environmental effects between men and women in educational attainment across the countries? Does GxSES differ by gender across countries?

First, the findings indicate that the contribution of genetic factors to educational attainment varies significantly across countries.

Finland, where educational tracking occurs later and the education system promotes equal opportunities, demonstrated the highest genetic component, followed by the Netherlands, Norway, and Germany. In contrast, shared environmental influences were most significant in Germany, supporting the hypothesis that an unequal educational context amplifies the role of the family environment. In Norway, we observed a larger shared environmental effect than in Finland, which contradicts our hypothesis about a higher genetic contribution of equal education systems, as the educational systems in Norway and Finland are very similar. The result reproduces the previous finding that the influence of shared environment is higher in Norway than in other Nordic countries (Baier et al., 2022). However, due to the smaller sample size in Norway, the shared environmental effects were not statistically significant between Norway and Finland. We only found GxSES in educational attainment in Finland, but not in the other countries. When measuring GxSES with the same birth cohorts, the same operationalizations of educational attainment, and parental SES across countries. This does not imply that SES and institutional context are unimportant for genetics in educational attainment in contexts outside of Finland, as we demonstrate that it could depend on gender. Moreover, different processes at the family and country levels could cancel each other out.

Second, we hypothesized that boys, on average, mature psychologically and biologically slower than girls. Therefore, the genetic effect would have been stronger for women, particularly in countries with early educational tracking systems like Germany and the Netherlands. We did not find significant gender differences in genetic and environmental components in any country. Thus, the analyses did not support the hypothesis that the genetic contribution to educational attainment would be smaller for males than for females.

The results for gender contradict the previous studies on older birth cohorts, which found that among women, environmental factors were higher and a genetic contribution lower in their educational attainment compared to men (Arpawong et al., 2023; Branigan et al., 2013; Silventoinen et al., 2004). The change in these influences between younger and older cohorts is likely due to the reduced social constraints on women over time (Herd et al., 2019). The absence of gender differences in the ACE components indicates that men and women in the cohorts born in 1980-1998 have equal genetic liabilities for educational attainment within the four countries.

Third, we hypothesized that both gender and institutional context moderate GxSES. We expected the timing of school tracking to primarily shape this interaction. In early-tracking systems (Germany and the Netherlands), men's educational attainment should be more strongly influenced by parental involvement and disadvantaged family events than women's. In late-tracking systems (Finland and Norway), we anticipated no gender differences. Our results, however, do not support this hypothesis. We found that the contribution of environmental components to educational attainment was higher for women from highly educated families than for those from low-educated families. The negative interaction for genetic effects (compensation) was observed in Finland, Norway, and Germany. For men, we found negative GxSES only in Finland, but not in any other countries. Thus, the gender difference in GxSES was not stronger in countries with early school tracking (i.e., the Netherlands and Germany); instead, the results were mixed across the institutional context.

Additionally, based on the idea of boys' greater environmental sensitivity (Hopcroft and Martin, 2016; Salminen and Lehti, 2023), we assumed that in the GxSES, the role of environmental components would be larger for men. In line with this expectation, we found that the shared environment contribution was greater among men with lower-educated parents than among those with higher-educated parents in Germany. This aligns with the mechanism whereby early school tracking may particularly influence men from low-educated family backgrounds.

Overall, our results indicate that GxSES can function differently based on gender and the institutional context. However, we did not find any clear patterns related to the different institutional features across countries. Future studies should recognize that GxSES are not necessarily uniform but may differ for men and women. Specifically, the underlying dynamics, considering additional factors such as cultural norms and policy changes, should be explored to further elucidate the mechanisms underlying the gene-environment interplay in educational attainment.

Furthermore, because our twin design cannot isolate trait-specific genetic effects— that would require polygenic scores—we are unable to distinguish the impact of advantageous genetic predispositions (e.g., high cognitive ability) from those associated with disadvantageous traits, such as behavioral or learning disorders. Future research should therefore examine how trait-specific polygenic scores related to behavioral disorders, such as ADHD, influence educational attainment across sexes and family backgrounds, and compare these effects with those associated with advantageous genetic predispositions.

Our study has its limitations. First, GxE requires a high statistical power to detect a significant interaction. Particularly, the Norwegian and German twin data are relatively small, which constrain the results for these countries. The observed variation in the ordering of A (genetic) and C (shared environmental) components across Finland, the Netherlands, Norway, and Germany may partly reflect differences in data availability and sampling. Finland and the Netherlands used population-wide register data, whereas the analyses for Norway and Germany relied on smaller survey-based samples. Smaller sample sizes in Norway and Germany lead to larger standard errors (e.g., A: Finland 67.6% $\pm$ 4.2%, Norway 46.2% $\pm$ 8.0%, Netherlands 53.1% $\pm$ 4.6%, Germany 35.8% $\pm$ 6.3%), which increases uncertainty in the estimates. Measurement error in E may also be slightly higher in survey-based samples, but the observed E percentages (Finland 24%, Norway 33%, Netherlands 34%, Germany 37%) do not suggest substantial inflation in Norway or Germany. Despite the methodological differences, we believe that our findings capture meaningful institutional differences as the variance components for Germany differ significantly from those of Finland, representing a comparison between the most divergent educational systems in our study. Thus, while design factors contribute to uncertainty, they are unlikely to fully account for the observed cross-national patterns.

Second, we lack direct measures of zygosity in Finland and the Netherlands. However, relying on large population-level datasets from Finland and the Netherlands, including not only twins but also siblings, addresses some concerns of using twin data, including representativeness. Moreover, previous research has shown that ACE estimates with unknown zygosity are comparable with the results when zygosity is explicitly known (de Zeeuw and Boomsma, 2017). Thus, the benefits of representativeness and larger sample sizes, crucial for modeling interactions, outweigh the limitations introduced by missing zygosity data.

Third, twin models include a crucial assumption, the equal environments assumption (EEA), meaning that environments are assumed to be equal between identical and fraternal twins. If this assumption is violated, shared environmental effects are mistakenly attributed to the genetic component; therefore, shared environmental effects would be underestimated. However, empirical studies have found minimal evidence that violations of the EEA bias heritability estimates (Conley et al., 2013; Mönkediek, 2021). Further, assortative mating is not accounted for in our models. This omission may lead to an underestimation of the genetic component and an overestimation of the shared environment component. Therefore, it can be assumed that our estimates are conservative in relation to genetic effects. Importantly, since rates of assortative mating are comparable across countries (see Table 2), it is unlikely to drive any country differences in our results.

Finally, the results of this study should be replicated using PGIs to advance the knowledge of the genetic effect of gender differences by parental background. Previous research using the PGI approach has shown consistent patterns, as our study did, about the gender differences in educational attainment. However, results are only from one country (Lahtinen et al., 2024). This study highlighted the complex interplay between genetic and environmental factors in educational attainment, influenced by family SES, gender, and institutional contexts.

CRediT authorship contribution statement

Hannu Lehti: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kim Stienstra:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Tina Baier:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Torkild H. Lyngstad:** Writing – review & editing, Investigation, Formal analysis, Data curation.

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Declaration of competing interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssresearch.2026.103375.

Data availability

The micro census register data used in the study are not available for public use. TwinLife data is available on request on their website: https://www.twin-life.de/. The Finnish data can be accessed by submitting a data access request to Statistics Finland: https://stat.fi/tup/tutkijapalvelut/kayttoluvan-hakeminen-ja-lupamuutokset_en.html. Results for Finland are based on calculations by Hannu Lehti under data license number: TK/2200/07.03.00/2025. Results for the Netherlands are based on calculations by Kim Stienstra in project number 9232 'Sociale ongelijkheid en veranderingen in levenslopen' using non-public microdata from Statistics Netherlands (CBS). Under certain conditions, these microdata can be accessed via the following link: https://www.cbs.nl/en-gb/our-services/customised-services-microdata/microdata-conducting-your-own-research. The Norwegian data can be obtained by application to Statistics Norway (administrative register data) and the Norwegian Institute of Public Health (the National Twin Register).The Nor-

wegian data from administrative registers and the National Twin Register were used via the project SUBPU, which is approved by the Regional Committees for Medical and Health Research Ethics (ref. 2017/2205). The University of Oslo is responsible for the data handling in SUBPU and has conducted a Data Protection Impact Assessment (DPIA) in collaboration with the Norwegian Agency for Shared Services in Education and Research (Sikt; ref. 962,088). The data access and management of SUBPU is financed by the Research Council of Norway (RCN), the European Research Council (ERC), and the Department of Psychology at the University of Oslo. This work was performed on the TSD (Tjenester for Sensitive Data) facilities, owned by the University of Oslo, operated and developed by the TSD service group at the University of Oslo, IT-Department (USIT). The work was performed on resources provided by Sigma2 - the National Infrastructure for High-Performance Computing and Data Storage in Norway (ref. NS9867S).

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