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Original Article

Genetic Influences on Educational Achievement in Cross-National Perspective

Tina Baier[1,*], Volker Lang[2], Michael Grätz [3,4], Kieron J. Barclay[5], Dalton C. Conley[6], Christopher T. Dawes[7], Thomas Laidley[8] and Torkild H. Lyngstad[1]

[1]Department of Sociology and Human Geography, University of Oslo, 0317 Oslo, Norway, [2]Department of Sociology, University of Tübingen, 72074 Tübingen, Germany, [3]Institut des Sciences Sociales, University of Lausanne, 1015 Lausanne, Switzerland, [4]Swedish Institute for Social Research (SOFI), Stockholm University, 10691 Stockholm, Sweden, [5]Max Planck Institute for Demographic Research, 18057 Rostock; Department of Sociology, Stockholm University, 10691 Stockholm; Swedish Collegium for Advanced Study, 75238 Uppsala, Sweden, [6]Department of Sociology, Princeton University, Princeton, NJ 08544, USA; National Bureau for Economic Research, Cambridge, MA 02138, USA, [7]Political Science Department, New York University, New York, NY 10012, USA and [8]Institute of Behavioral Science and Institute for Behavioral Genetics, University of Colorado, Boulder, CO 80303, USA

*Corresponding author. Email: tina.baier@sosgeo.uio.no

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Abstract

There is a growing interest in how social conditions moderate genetic influences on education [gene–environment interactions (GxE)]. Previous research has focused on the family, specifically parents' social background, and has neglected the institutional environment. To assess the impact of macro-level influences, we compare genetic influences on educational achievement and their social stratification across Germany, Norway, Sweden, and the United States. We combine well-established GxE-conceptualizations with the comparative stratification literature and propose that educational systems and welfare-state regimes affect the realization of genetic potential. We analyse population-representative survey data on twins (Germany and the United States) and twin registers (Norway and Sweden), and estimate genetically sensitive variance decomposition models. Our comparative design yields three main findings. First, Germany stands out with comparatively weak genetic influences on educational achievement suggesting that early tracking limits the realization thereof. Second, in the United States genetic influences are comparatively strong and similar in size compared to the Nordic countries. Third, in Sweden genetic influences are stronger among disadvantaged families supporting the expectation that challenging and uncertain circumstances promote genetic expression. This ideosyncratic finding must be related to features of Swedish social institutions or welfare-state arrangements that are not found in otherwise similar countries.

Introduction

Education is one of the most important predictors for an individual's life chances. Genetic influences on education are well-established (e.g. Nielsen, 2006; Branigan, McCallum and Freese, 2013; Belsky *et al.*, 2016; Lee *et al.*, 2018). However, their importance can vary across social contexts since individuals realize their genetic potential in constant exchange with environmental conditions (Bronfenbrenner and Ceci, 1994).

Previous research on the moderation of genetic influences on education by the social context mainly focused on the quality of the family context, notably parents' social standing. A smaller body of literature discusses the importance of macro-level institutions, such as the educational system and the welfare state (Heath *et al.*, 1985; Diewald, 2016; Selita and Kovas, 2019). Some studies found that genetic influences were relatively stronger in more egalitarian educational settings and countries with more social mobility (Heath *et al.*, 1985; Tambs *et al.*, 1989; Branigan, McCallum and Freese, 2013; Lin, 2020), while other studies provided counter-evidence (Baker *et al.*, 1996; Morris, 2020; Silventoinen *et al.*, 2020).

What is missing are comparative studies that systematically analyse whether differences in welfare states and educational systems shape genetic influences on education using an harmonized research strategy across countries. We provide such an analysis and combine the two branches of studies on gene–environment interactions (GxEs), i.e. studies on conditions set by the family (micro-level) and those that look at institutional arrangements (macro-level). Specifically, we address the following two research questions: First, *do overall genetic influences on educational achievement differ across Germany, Norway, Sweden, and the United States*? And second, taking interdependencies between national and family contexts into account, we ask *whether a possible social stratification of genetic influences on education differs across these countries?*

On a theoretical level, we incorporate the comparative social stratification literature into genetic research. Specifically, we form our expectations on cross-country variation in genetic influences by focusing on the timing of tracking and the generosity of the welfare state. We link these macro-structural features to well-established GxE-conceptualizations: the enhancement mechanism, and the challenging mechanism. The first emphasizes the importance of enriched social conditions for the realization of genetic potential (Bronfenbrenner and Ceci, 1994; Shanahan and Hofer, 2005). The second focuses on the challenges and uncertainties associated with impoverished social conditions that stimulate genetic expression (Saunders, 2010; Nielsen, 2016; Lin, 2020).

We base our empirical analysis on large-scale, high-quality survey data on twins for Germany (German Twin Family Panel 'TwinLife') and the United States (National Longitudinal Study of Adolescent to Adult Health 'Add Health', and the Minnesota Twin Family study 'MTFS') as well as population registers on twins for Norway and Sweden. We measure educational achievement with school grades and estimate genetically sensitive variance decompositions (i.e. ACE models). The birth cohorts of the twins we study range from 1972 to 1993.

Our findings on cross-national differences in genetic influences on education are also informative for current debates about the openness of a society's opportunity structure. Some have argued that the heritability of education—i.e. the amount of variation in education associated with genetic as opposed to environmental factors—represents an illegitimate source of social closure as one cannot control what kind of genes one receives from the parents (Solon, 2004). This perspective has been countered by scholars that argue that the heritability can actually be seen as an indicator for the openness of a society (e.g. Guo and Stearns, 2002; Nielsen, 2006; Diewald *et al.*, 2015): to the extent that genes represent merit or talent one would expect that more open societies, i.e. societies with lower social barriers to education, provide more room for genetic potential to unfold and have consequently a higher heritability of education.

We contribute to the literature by providing a theoretically grounded, small-N, cross-national comparison of genetic influences on educational achievement and their possible stratification across Germany, Norway, Sweden, and the United States. Using the same analytical approach, similar definitions of variables, and high-quality twin data for each of the countries, enables us to contextualize GxEs with distinct combinations of welfare-state regimes and educational systems.

Theoretical Framework

The bio-ecological model states that human development takes place in stable exchange with environmental conditions, called 'proximate processes', provided at various contextual levels, such as the family or close networks but also more distant levels, such as institutional arrangements (Bronfenbrenner and Ceci, 1994). Thus, even though the genetic endowments we inherit are mostly fixed, whether or to what extent they are realized depends on the social influences we encounter (Shanahan and Hofer, 2005). To conceptualize how more distal environmental influences located at the macro-level moderate genetic influences on education, we refer to the enhancement and the challenging mechanisms, as well as to social ascription as factors that are crucial to understand genetic influences on education.

Enhancement describes how stable exchange with enriched social settings helps individuals to tap their genetic potential (Bronfenbrenner and Ceci, 1994; Shanahan and Hofer, 2005). To date, this mechanism has been mostly located at the family context. This line of research motivates the Scarr–Rowe hypothesis, which claims that genetic effects on intelligence are stronger among high socio-economic status (SES) families (Scarr-Salapatek, 1971; Rowe, Jacobson and Oord, 1999). These studies link the enhancement mechanism to social background by arguing that socioeconomically advantaged parents provide rearing conditions and resources that facilitate the realization of genetic potentials for cognitive abilities and, more recently, education (e.g. Turkheimer *et al.*, 2003; Conley *et al.*, 2015; Baier and Lang, 2019; Lin, 2020).

Instead of focusing on the complementarity between favourable genetic endowments and social conditions, scholars have also stressed the substitutive function of genetic potentials in situations marked by unpredictability and instability. Uncertainties represent a challenge and individuals have to rely more strongly on their genetic potential to successfully master such situations (Saunders, 2010; Nielsen, 2016; Lin, 2020). This mechanism motivates the Saunders-hypothesis, which proposes the opposite trend as the Scarr–Rowe hypothesis, namely that genetic influences are stronger in less favourable conditions, i.e. low-SES families (ibid.). We label this mechanism *challenging mechanism*.

On the macro-level, welfare-state arrangements can be viewed as an important moderator of social background effects on status related outcomes, such as education (e.g. Nolan *et al.*, 2010; Esping-Andersen and Wagner, 2012; Esping-Andersen, 2015; Grätz *et al.*, 2021). Previous research shows, for instance, that the Scandinavian countries were comparatively successful in reducing social background effects among disadvantaged groups (Esping-Andersen, 2015). In light of such interdependencies between family-level influences and the welfare-state regimes, childrens' chances for the development of genetic potential for education may vary accordingly (Diewald, 2016; Selita and Kovas, 2019).

With respect to macro-level moderation of genetic influences on education it is furthermore important to acknowledge that education is substantially influenced by social ascription. Education, therefore, differs from embodied characteristics, such as cognitive and non-cognitive skills (Freese and Jao, 2017). Social ascription effects influence educational choices over and above an individual's abilities (e.g. Erikson and Jonsson, 1996; Breen and Goldthorpe, 1997). These choices lead to different educational environments and are decisive in determining to what extent individuals can realize their genetic potential. Consequently, to understand differences in genetic influences on education it is important to consider the social selectivity of the educational system.

The Stratification of the Educational System: The Timing of Tracking

The structure of an educational system regulates access to learning environments. Educational tracking means the formal selection of students into different schools, tracks, or programmes based on their academic performance (e.g. Bol *et al.*, 2014). The purpose of separating students based on ability is to facilitate teaching conditions and content in line with students' needs. Such tailored environments supposedly provide optimal learning conditions for all students. Previous findings, however, show that students do not all benefit equally from being tracked (Van de Werfhorst and Mijs, 2010): students that start at lower competence levels tend to be negatively affected, while educational gains for high-achieving students are relatively small.

Tracking is a common feature of Western educational systems but countries differ considerably in the age at first tracking. In some countries, such as the Nordic countries, students are not tracked until the end of compulsory schooling, around the age of 16. In contrast, other countries, notably most German federal states, already sort their students around the ages 10–12 into vertically differentiated school tracks. The earlier that tracking takes place, the more difficult it is to assess children's educational performance and to sort them into the 'right' track (Brunello, Giannini and Ariga, 2007). Relatedly, children's cognitive skills and educational performance early in childhood are more strongly related to social background compared to later in childhood or adolescence (Dustmann, 2004; Ammermueller, 2013; Pekkala Kerr, Pekkarinen and Uusitalo, 2013).

Educational tracks differ qualitatively due to institutional and compositional aspects (Maaz *et al.*, 2008; Horn, 2013): lower school tracks follow a less demanding curriculum, which is often coupled with less funding and less experienced teacher personnel. Furthermore, lower school tracks are predominantly attended by students from less advantaged social backgrounds. Low achieving students may, however, benefit from learning in mixed-ability groups, and could in turn miss the stimulating learning environment provided by high-achieving peers (Zimmer and Toma, 2000).

Previous comparative research shows that the institutional set-up of an educational system, specifically the strictness and the age at first tracking, affects children's educational achievement (e.g. Hanushek and Wössmann, 2006; Horn, 2009; Ammermueller, 2013). Differences across tracks in learning environments can not only be linked to children's educational performance but also to their chances to realize their genetic potential.

Adopting the enhancement mechanism, which focuses on the stimulating function of enriched environments for genetic potentials, higher educational tracks represent more stimulating and enriched learning environments, which foster genetic influences on education. Lower educational tracks, by contrast, can be viewed as environmental constraints that restrict the realization of genetic potentials. In this perspective, the limiting effects of early tracking on children's academic growth seem to outweigh the benefits from learning in more performance-homogenous groups. Consequently, genetic influences on education should be smaller in early-compared to late-tracking systems.

The challenging mechanism leads to the same conclusion but for a different reason. Here, the focus is on the demanding circumstances linked to the postponement of the tracking decision. The later students are sorted into educational tracks, the longer they are confronted with uncertainty about the development of their educational career. In addition, students are longer exposed to stress, as they have to proof themselves and demonstrate their abilities until the tracking decision is made. If, by contrast, students are tracked early in their educational career, tracking decisions are more or less fixed as switches between educational tracks represent rather an exception than the rule, and are furthermore associated with parents' social background (Henz, 1997; Dustmann, 2004; Jacob and Tieben, 2009). Additionally, students often do not even try to correct their tracking decision as being tracked in the lowest track severely lowers their self-esteem (Knigge, 2009; Spruyt, Van Droogenbroeck and Kavadias, 2015). Together, students have to rely stronger on their genetic potential to successfully manoeuver themselves through the educational system, if decisions are made late in the educational career, which increases genetic influences on education.

Welfare-State Generosity: Institutionalized Social Protection

The rearing environment that parents provide for their children depends not only on the individual characteristics of the parents but also on the macro-institutional framework they are embedded in. Especially, the configuration of welfare states shapes overall living standards and provides different protection for individuals in case of exposure to life risks (Esping-Andersen, 2015). Importantly, redistributive policies not only affect the (socioeconomic) well-being of the person who is hit by adverse life events but also the well-being of their families (e.g. DiPrete and McManus, 2000; DiPrete, 2002).

The macro-sociological comparative literature typically differentiates between three different welfare regimes: Liberal, conservative, and social-democratic (Esping-Andersen, 1990, 1999). The liberal welfare regime is characterized by low levels of state intervention. The social-democratic welfare regime has comparably high levels of redistribution and universal access to both health care and education, as well as a more encompassing social security net. In the conservative welfare regime social protection is strongly coupled with previous employment and related contributions.

Welfare regimes apply different strategies in trying to prevent negative consequences of adverse life events (DiPrete, 2002): One strategy focuses on reducing the frequency of risky life events, and the other strategy tries to mitigate the negative consequences through redistributive policies. The conservative welfare regime is successful in suppressing adverse events but does not provide uniformly protection against the negative consequences, while the opposite holds for the social-democratic welfare regime. By contrast, the liberal welfare regime does neither suppress the rate of events nor its consequences. Thus, individuals in liberal welfare regimes more often face spells of severe economic insecurity compared to individuals from conservative and social-democratic welfare state (DiPrete and McManus, 2000; DiPrete, 2002).

The resulting economic deprivation, exposure to stress, and unpredictability of living standards in the liberal welfare state is likely to limit parents capacity to provide rearing environments tailored to their children's needs. Such discontinuities and the lack of material and non-material resources can lower developmental opportunities for children. Previous comparative research on parental unemployment, for instance, shows that the intergenerational consequences on children's education are less severe in countries with higher levels of institutionalized protection (Lindemann and Gangl, 2020). Consequently, the protective function of the welfare state improves the quality and stability of the family environment indirectly.

Linking such adverse and unstable living conditions to the development of genetic potential leads to two opposing expectations: from the enhancement perspective, higher levels of institutionalized protection foster the realization of genetic potentials. Consequently, genetic influences on education should be weaker in liberal welfare regimes, which largely lack such protective features. Yet, these unfavourable living conditions are exactly those that provoke the realization of genetic potential according to the challenging mechanism. Individuals have to rely heavily on their own resources and genetic endowments represent a major source to cope with adversities. Consequently, genetic influences should be stronger in liberal welfare-state regimes.

Institutional Contexts, Parents' Socioeconomic Standing, and Genetic Influences

The family context is arguably most directly linked to children's development and the above discussed concepts: enhancement, environmental challenges, and social ascription. Specifically parents' SES has been acknowledged in previous studies on GxE for education. It has, however, been neglected that their impact can differ across educational systems and welfare states.

Comparative stratification research shows that the association between social background and children's education is particularly strong in early tracking systems and that early tracking limits the developmental opportunities for disadvantaged children (e.g. Müller and Karle, 1993; Breen and Jonsson, 2005; Pfeffer, 2008; Van de Werfhorst and Mijs, 2010; Jackson and Jonsson, 2013). The timing of tracking, therefore, moderates children's chances for educational growth and possibly the genetic influences on education.

Applying the enhancement perspective one would expect that the impact of parents' socio-economic standing on children's chances to realize their genetic potential is more pronounced in early tracking systems (see also Baier and Lang, 2019). This can be explained in light of primary effects that describe how advantaged parents foster the skill formation of their children by providing various kinds of material and non-material resources (Boudon, 1974). Initial (dis-)advantages due to social background tend to be reinforced in early tracking systems: advantaged children enjoy better learning environments at home and attend more often higher educational tracks, which represent resource-rich and more stimulating learning. Such environmental conditions foster genetic expression leading to stronger genetic effects among advantaged compared to disadvantaged children.

The challenging mechanism leads to the opposite expectation, namely that the social stratification is more pronounced, the later tracking takes place, and that genetic influences are stronger among disadvantaged children. Disadvantaged children have an even harder time in meeting the higher demands and uncertainties associated with late tracking as they are less likely to receive support from their parents. Advantaged parents have strong preferences to maintain their social status (e.g. Breen and Goldthorpe, 1997) and may as well provide additional resources to compensate for lower abilities of their children to maintain their social status. Thus, disadvantaged children are more dependent on their genetic potential to successfully navigate through the educational system while advantaged children are more likely to receive support from their parents.

Developmental consequences associated with social background may also differ across welfare regimes. Individuals in liberal welfare regimes more often encounter adverse life events such as unemployment and divorce while the welfare state does little to mitigate the negative consequences (DiPrete, 2002). Due to the lack of societal buffering mechanisms, parents' social standing and related resources play a stronger role in how well parents can handle adverse living conditions and protect their children from its consequences. Advantaged parents can survive for at least some time on their savings or have a social network to rely on, so that they are still able to provide rather stable living conditions for their children even if one parent experiences a negative life event. Among already disadvantaged families, adverse spillover effects from parents' economic situation to their children may be stronger because parents have fewer means to compensate for the economic loss or to cope with stress. This expectation is supported by research that indicates that the intergenerational consequences of unemployment are stronger among less educated parents (Lehti, Erola and Karhula, 2019; Lindemann and Gangl, 2020).

Applying the enhancement perspective one would expect that the social gradient in line with the Scarr–Rowe hypothesis is more pronounced in liberal welfare regimes due to the lack of stimulating rearing environments, which is more concentrated among already disadvantaged families. In contrast, the challenging mechanism proposes that the social stratification is stronger in liberal welfare regimes, as children have to rely stronger on their genetic potential under impoverished rearing environments leading to stronger genetic influences among disadvantaged children.

Findings from Previous Research

Several studies indicated that genetic influences on education respond to macro-institutional change: Twin-based studies from Norway reported that genetic influences on education increased over the second half of the

20th century (Heath *et al.*, 1985; Tambs *et al.*, 1989). This result has been explained by the introduction of more egalitarian educational policies. Recent findings for the United States based on polygenetic scores (Lin 2020) and an international meta-analysis based on twins from Western industrialized countries supported the conclusion (Branigan, McCallum and Freese, 2013). However, twin-based findings for Australia and a recent international twin study could not replicate these results (Baker *et al.*, 1996; Silventoinen *et al.*, 2020).

Some studies have also provided evidence for cross-country differences in genetic influences on education. The systematic literature review by Selita and Kovas (2019) found, for instance, that genetic influences on education were weaker in countries with higher income inequality (a finding which they labelled ‘Gene-Gini Interplay’). This finding suggests that social policies can influence individuals’ chances to express their genetic potential for education and support our reasoning about the importance of the welfare regimes. In line with this expectation, Engzell and Tropf (2019) found that genetic influences were stronger in egalitarian contexts with higher social mobility. However, a follow-up analysis argued that methodological choices may have driven this conclusion (Morris, 2020).

With respect to the importance of parents’ social standing, twin-based results for Germany and Finland confirmed the Scarr–Rowe hypothesis for education (Baier and Lang, 2019; Erola *et al.*, 2021). Research from Norway, however, based on polygenic scores (PGS) did not find systematic differences across the social strata (Isunget *et al.*, 2021). For the United States, recent PGS findings for education were in line with the Saunders-hypothesis (Lin, 2020) while findings from Conley *et al.* (2015) and Domingue *et al.* (2015) based on older and less predictive PGS provided inconclusive results.

To sum up, there is some indication that genetic influences on education are stronger in countries with egalitarian educational systems and more generous welfare-state regimes but evidence is mixed. With respect to the social stratification, evidence is even less clear as findings differ across similar institutional settings. Overall, the literature is marked by methodological differences, notably differences in cohorts, study design, and analytical strategies, all of which are likely to contribute to divergent findings. Neither has the previous literature systematically examined whether differences in welfare regimes or the educational system shape the overall strength of genetic influences on education and their stratification.

Comparative Study Design and Hypotheses

We compare genetic influences and their social stratification across Germany, Norway, Sweden, and the United States. These countries differ in their educational systems and represent the three different types of welfare regimes, which are often used in internationally comparative social inequality research. We analyse school grades as an indicator of educational achievement for twins born between the years 1972 and 1993.

Germany has an early tracking system, which sorts children as early as age 10–12 (depending on the federal state). In the United States, compulsory education is comprehensive, but students are often sorted into courses that differ in their required level of performance (internal tracking) (Lucas, 1999). In addition, there is substantial regional variation in the regulation and quality of education. The educational systems in the Nordic countries are known for their comparatively egalitarian accessibility and homogenous quality. Here, tracking is absent from compulsory schooling. While there are some differences in the educational systems of Norway and Sweden, differences occur mainly with respect to the organization of the upper secondary level (Lundahl, 2016). Taken together, Norway, Sweden, and the United States have longer periods of comprehensive schooling and less strict tracking than Germany (Bol *et al.*, 2014).

The German welfare state largely represents the conservative welfare regime. Sweden and Norway are social-democratic welfare regimes while the United States represent the liberal welfare regime (Esping-Andersen, 1990, 1999). Our comparative research design enables us to examine how genetic potential unfolds in two similar institutional settings, which have comprehensive schooling and a generous welfare state (Norway and Sweden) in comparison to settings, which either lack comprehensive schooling (Germany) or protective social policies (United States) (Table 1). In the Supplementary Material, we demonstrate that major differences in the timing of educational tracking and the generosity of welfare-state regimes across countries have remained stable during the observation period of our study (Supplementary Tables SA1 and SA2).

Based on these macro-level differences, we derive the following expectations: applying the *enhancement mechanism*, we hypothesize that genetic influences on educational achievement are stronger in Norway and Sweden than in Germany and the United States because of Norway’s and Sweden’s relatively egalitarian educational system and more generous social protection that

Table 1. Expectations about overall genetic influences on education and their social stratification

	Institutional conditions	
	Early tracking	WFS generosity
Countries		
Germany (GER)	+	+
Norway (NO)	−	+
Sweden (SW)	−	+
United States (US)	−	−
	Expectations	
	Overall	**Social stratification**
GxE-conceptualization		
Enhancement mechanism	H1a: NO, SW > GER, US	H2a: Scarr–Rowe hypothesis NO, SW < GER, US
Challenging mechanism	H1b: US>NO, SW > GER	H2b: Saunders-hypothesis US>NO, SW > GER

can be considered as contextual features that further the development of genetic influences. The related Scarr–Rowe hypothesis should be more marked in Germany because of early tracking, and similarly in the United States because of the less developed welfare state and low levels of institutionalized social protection.

Applying the *challenging mechanism*, we hypothesize that genetic influences are most pronounced in the United States because of late educational tracking coupled with low levels of institutionalized protection; and least pronounced in Germany due to both early tracking as well as higher levels of social protection. Norway and Sweden are set in between because of late tracking and generous social protection. The social gradient in line with the Saunders-hypothesis should follow the same country ordering, i.e. stronger in the United States, followed by the Nordic countries, and less pronounced in Germany.

Data, Measures, and Methods

We use high-quality data from twin surveys for Germany and the United States, and twin data from population registers for Norway and Sweden. For Germany, we use the German Twin Family Panel (TwinLife) (Mönkediek *et al.*, 2019). TwinLife started in 2014/2015 and provides a population register-based sample of monozygotic (MZ) and same-sex dizygotic (DZ) twins and their families in Germany. For the United States, we use the National Longitudinal Study of Adolescent to Adult Health study (Add Health), a nationally representative sample of adolescents in grades 7–12 during the 1994/1995 school year. Besides the core sample, we use the oversample of siblings (including MZ and DZ twins) (Harris *et al.*, 2006, 2013). Due to the small sample size, we additionally analyse the Minnesota Twin Family Study (MTFS) (Iacono and McGue, 2002). The MTFS provides a population-based sample of MZ and same-sex DZ twins aged 11 or 17. Twins are broadly representative for the corresponding birth cohorts of Minnesota. For Norway, we use a register dataset based on the Norwegian Twin Registry (Nilsen *et al.*, 2016), and for Sweden, we use the multigenerational registers that allows us to link twins to their parents. Unfortunately, we miss information about twins' zygosity in Sweden. We address unknown zygosity in the ACE models by (i) using sex as proxy for zygosity and (ii) by standardizing school grades within twins' gender (e.g. Scarr-Salapatek, 1971; Figlio *et al.*, 2017; Zeeuw and Boomsma, 2017) (see Supplementary Material SA3). Previous research demonstrated that ACE results based on our approach are comparable to those that are estimated based on known zygosity (Zeeuw and Boomsma, 2017). Thus, the limitation of missing zygosity is outweighed by the advantages to include Sweden: first, Sweden can be perceived as institutionally similar to Norway. Second, the data set-up is comparable to Norway. Having an additional representant of the Nordic countries increases the validity and external generalizability of our results (e.g. Lijphart, 1971).

Measures

We analyse educational achievement indicated with grade point averages (GPA). In Sweden and Norway, we

Table 2. Overview of the datasets, birth cohorts, observation period, twins' age, measurement of GPA, and sample sizes

Country	Dataset	Birth cohorts	Observation period	Twins' age	Measurement of GPA	Twin pairs
Germany	TwinLife	1990–1993	2014–2015	21–26 (retrospective)	End of secondary education age: 16–19[a,b]	848
Norway	Register data	1986–1991	2002–2007	16	End of lower secondary age: 16[a]	903
Sweden	Register data	1982–1991	1998–2007	16	End of lower secondary age: 16[a]	6,510
United States	Add Health	1976–1982	2001–2002	18–25 (retrospective)	End of secondary education age: 18–19[a]	364
	MTFS	1972–1994	1989–2004	19–20 (retrospective)	End of secondary education age: 18–19[a]	1,484

[a]Age refers to the average age of graduation.
[b]School tracks in Germany differ by length explaining the age range of 3 years.
Sources: TwinLife (Germany), Norwegian Registers, Swedish Registers, and Add Health and MTFS (United States).

measure GPA at the end of compulsory schooling, which refers to lower secondary education, and in the United States at the end of high school that is upper secondary education. In Germany, due to the tripartite education system, we measure GPA either at the end of lower secondary ('Hauptschule'), intermediate secondary ('Realschule'), or upper secondary schooling ('Gymnasium'). Table 2 displays basic information on the datasets and measurement of GPA. We harmonized the scale of GPA across countries so that higher values indicate a better GPA and z-standardized GPA to facilitate the comparability across countries.

In the Supplementary Material SA4, we describe in detail how we measured GPA in each country. For Germany, however, it is important to note that we corrected for differences in the hierarchically structured school tracks. Since the highest secondary school track ('Gymnasium') is the most demanding, we subtracted one grade if a student graduated from the intermediate ('Realschule') and two grades if a student graduated from the lowest school track ('Hauptschule'). We provide a formular for the adjustment as well as sensitivity analyses for different types of adjustments, ranging from −0.5 to 1.5 in the Supplementary Material SA5. The results demonstrate that our findings on genetic influences are not driven by our adjustment.

Despite our efforts to make GPA as comparable as possible across countries, the age of measurement differs. Age differences are due to (i) cross-country differences in the set-up of secondary education and (ii) differences between the registers and survey data as we observe GPA later than it was actually achieved in Germany and the United States. In these countries, we rely on twins' retrospective information. Consequently, recall error as well as life course variation in countries with survey data may affect our findings and comparative conclusions. However, it is unlikely that recall error affects our results substantially since graduation from secondary education marks a major life event during early adolescence and GPA is crucial for the subsequent educational or occupational career. Given that students are still in their early to mid-twenties when they report their GPA, it seems fair to assume that they remember it quite accurately.

Differences in the age at which GPA is measured (16 in Norway and Sweden, 18–19 in the United States, and 16–19 in Germany) may affect our results. Life course variation in genetic influences on IQ, for instance, is well-established. Research shows that genetic influences increase linearly from early childhood to adulthood and stay rather stable after age 20 explaining approximately four-fifth of the variation in IQ (Haworth *et al.*, 2010; Bouchard, 2013). However, we expect that differences in age do not substantially affect our results because genetic influences on GPA are not only related to IQ but include also those related to non-cognitive skills, such as self-efficacy or motivation (Krapohl *et al.*, 2014). While the age-gradient for these traits is less studied, the heritability of non-cognitive skills is generally smaller than for IQ. In addition, the age variation in our sample of three years is rather small.

We used parents' highest level of education (dominance principle) to measure socio-economic background. We chose education as indicator because it captures not only economic but also cultural resources and institutional knowledge, which are all relevant for educational choices (De Graaf, De Graaf and Kraaykamp, 2000; Buis, 2013). Additionally, education was easier to harmonize across countries than the country specific occupational codes. We transformed the categorical information on educational degrees into years of education. Specifically, we differentiated between basic, upper secondary (vocational track), upper secondary (academic track), post-secondary non-tertiary, and tertiary level education, and assigned 9, 11, 12, 14, and 15.5 years of education for the corresponding levels (see Supplementary Table SA6 for the coding scheme and SA7 describes how we dealt with missing values). Descriptive statistics by country and zygosity are displayed in the Supplementary Table SA8.

Analytic Strategy

We use the Classical Twin Design (CTD) to estimate genetic influences on school grades (Plomin *et al.*, 2008). The CTD assumes that DZ twins share on average 50% of the genes on which humans vary, while MZ twins are genetically identical. Based on these assumptions the CTD decomposes the total variance of an outcome in additive genetic influences (A), shared environmental influences (C), and unique environmental influences including measurement error (E). This variance decomposition method is known as ACE model. For our analysis, we use a multilevel mixed-effects specification (see Supplementary Material SA9).

The CTD relies on additional assumptions. For educational achievement the relevant assumptions are, first, random mating, and, second, the absence of gene–environment correlations and interactions. The remaining assumptions of no epistasis and equal environments assumption are addressed in the Supplementary Material SA10.

The CTD assumes that spouses mate randomly. If there is assortative mating with respect to the characteristic under study, then the average genetic similarity of DZs will be higher, and consequently genetic influences underestimated. Since assortative mating based on education is well-established (Blossfeld, 2009), we adjust or estimates for assortative mating (see Supplementary Material SA11).

Furthermore, the CTD assumes that genetic and environmental influences neither correlate nor interact. We address possible GxEs when we investigate whether genetic influences are socially stratified. The subgroup analyses reveal the extent to which genes and environment operate differently within these groups. This modelling approach is known as non-parametric GxE analysis (Guo and Wang, 2002). In contrast to parametric GxE models (e.g. Turkheimer *et al.*, 2003), non-parametric approaches do not impose a specific functional form. On the downside, non-parametric approaches have less statistical power due to lower sample sizes.

Results

We first estimated ACE models for each country-sample to examine cross-national variation in genetic influences on educational achievement (overall-hypothesis 1a and 1b). Figure 1 shows how genetic influences (A) and shared environmental influences (C) contribute to differences in school grades in Germany, Norway, Sweden, and the United States (see Supplementary Table SA12 for the estimation results). The left panel adjusts for assortative mating, and the right panel assumes that parents mate randomly.

Since the variances in educational achievement are *z*-standardized within each country, we present only the variance components in per cent (standardized variance components) and the related 95% confidence intervals. If the percentage of shared environmental influences was not statistically different from zero and smaller than 5%, we estimated AE models instead of ACE models. In these cases, Figure 1 only shows the variance associated with genetic influences.

The results show that genetic influences contribute substantially to differences in school grades in all countries as they account for more than half of the total variance. Accounting for assortative mating (Figure 1, left panel), shared environmental influences are only of relevance in Germany and in Norway. In Germany, genetic influences account for about 60% of the total variance in school grades. In Norway, Sweden, and the United States genetic influences are significantly larger as they account for approximately 75–85% of the total variance. Shared environmental influences are absent in Sweden and in both samples for the United States, while they account for 18% and 15% of the total variance in Germany and Norway.

The assumption of random mating yields comparable cross-country differences (Figure 1, right panel). Overall, genetic influences are about 10–20% larger and shared environmental influences are about 10–20% smaller. Because assortative mating exists in all countries (Supplementary Material SA11) the estimates adjusted for assortative mating represent the more realistic scenario.

Together, our results on cross-country differences are neither fully in line with the expectations based on the enhancement- nor the challenging mechanism. The only expectation that is clearly supported is the limiting effect

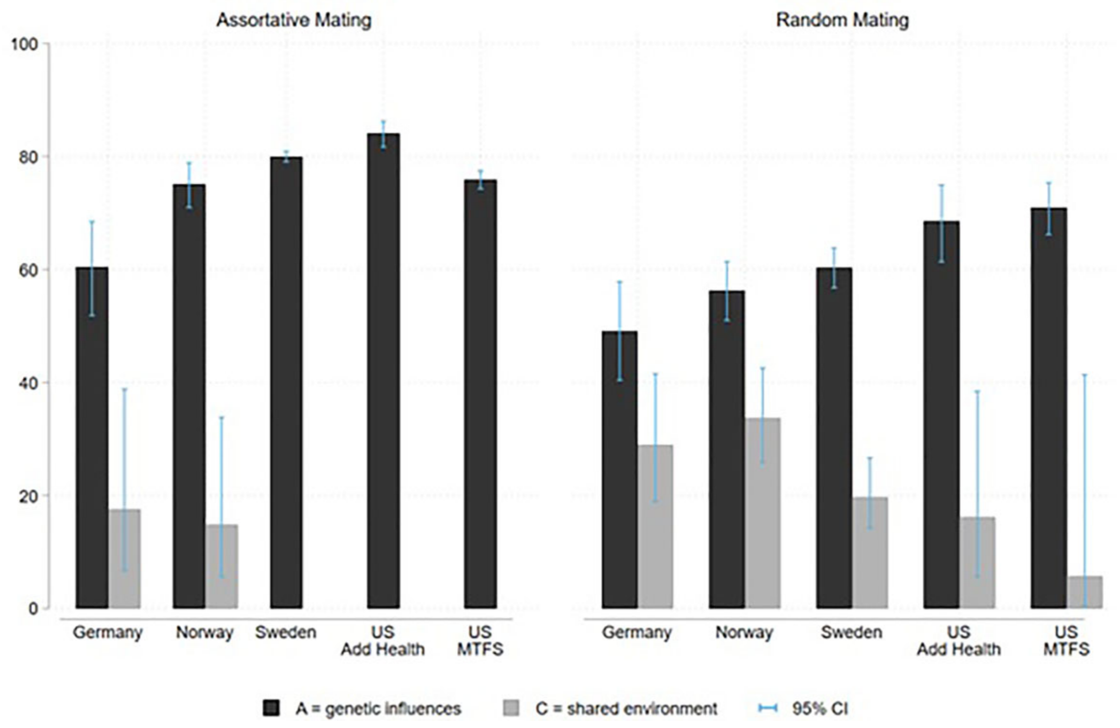

Figure 1. ACE results for twins' school grades—left panel: adjusted for assortative mating of parents; right panel: assuming random mating of parents.

Sources: TwinLife (Germany), Norwegian Registers, Swedish Registers, and Add Health and MTFS (United States).

of early tracking since genetic influences are least pronounced in Germany compared to the countries with longer periods of comprehensive schooling. This has been proposed by both mechanisms. However, the similarity in genetic influences on educational achievement among the United States and the Nordic countries, as well as the differences between Norway and Sweden come unexpected given our conceptual framework. Those genetic influences are comparatively strong in the United States and of similar size compared to the Nordic countries which may hint at a less important role of the welfare regime for genetic expression.

Next, we tested whether the social stratification of genetic influences differs across countries (Socialstratification hypothesis 2a and 2b) and stratified each country-sample by parents' education. Figure 2 visualizes the findings on the standardized variance components (see Supplementary Table SA13 for the estimation results). We elaborate on relevant differences between standardized and unstandardized variance components below.

Our results first confirm the well-established finding that school grades increase with parents' education (mean values, Supplementary Table SA13): twins from less educated parents have worse school grades than twins whose parents have higher levels of education.

We find for Norway and to some extent for Germany that genetic influences (standardized variance components) are less important among less educated parents. In Norway, there is a linear trend as the relative importance is about 54% in less-, 70% in medium-, and 75% in highly educated families. For Germany, the results follow an inverted U-shape as genetic influences account for about 52% in less-, 74% in medium-, and 48% in highly educated families. However, differences in genetic influences are not statistically significant in either of these countries. In addition, lower genetic influences among less educated families are not confirmed by the unstandardized variance components (Supplementary Table SA13). The unstandardized variance components can be derived by multiplying the standardized components with the respective total variance. For Germany, genetic influences are $1.3 \times 0.5 = 0.7$ in less-, and $0.8 \times 0.7 = 0.6$ in medium educated families; for Norway $1.0 \times 0.5 = 0.5$, and $0.9 \times 0.7 = 0.6$, respectively. In both countries, the total variance of school grades is higher among less educated families, which is mainly due to the

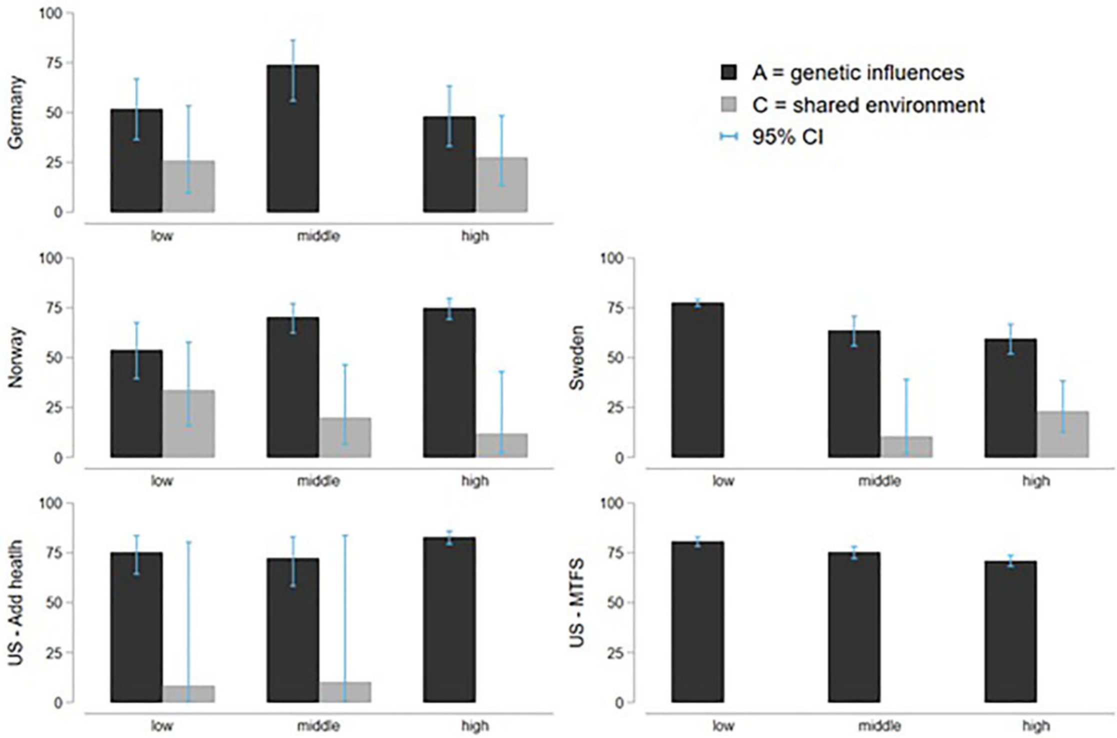

Figure 2. ACE results for twins' school grades by parents' education.

Sources: TwinLife (Germany), Norwegian Registers, Swedish Registers, and Add Health and MTFS (United States).

substantial impact of shared environmental influences (more than 25%). Thus, if anything the findings in Germany tend in the direction of the Saunders-hypothesis but the decline from medium- to highly educated families is neither substantial ($0.8 \times 0.7 = 0.6$ in medium-, and $0.7 \times 0.5 = 0.4$ in highly educated families) nor statistically significant.

Sweden is the only country where we identify a significant stratification pattern. The relative importance of genetic influences is most pronounced (approximately 80%) in less educated families, 65% in medium-, and 60% in highly educated families. This supports the Saunders-hypothesis. The results for the United States based on the MTFS data tend in the same direction but the differences are overall small in size ranging from about 80% in less educated families to 70% in highly educated families. Nevertheless, differences in the relative importance of genetic influences are statistically significant. That differences are significant in the MTFS data but not in the other samples is likely to be driven by the larger sample sizes of the educational subgroups coupled with the commonly smaller standard errors for AE compared to ACE models. In addition, results based on the nationally representative dataset (Add Health) show no differences by educational background in the United States.

In conclusion, the results for the social stratification do not follow either of the proposed country-orderings, which is not too surprising given that our expectations on the overall differences across countries have not been clearly supported either. We only find support for the Saunders-hypothesis in Sweden but not in Norway, which corresponds with our diverging overall findings for these countries.

Discussion and Conclusions

This study has evaluated whether differences in educational tracking and the generosity of the welfare state shape children's chances to tap their genetic potential for educational achievement. We linked differences in those macro-structural influences to the enhancement- and challenging mechanism and elaborated how social conditions moderate genetic influences and their social stratification. The enhancement mechanism focuses on enriched settings that stimulate the realization of genetic potentials, and the challenging mechanism on the uncertainty associated with disadvantaged conditions. In relation to both mechanisms, we acknowledged that educational choices and the exposure to learning environments depend on parents' social background.

Comparing Germany, Norway, Sweden, and the United States, we provide evidence for cross-national variation in overall genetic influences on educational achievement. In line with our expectations, we found that genetic influences on school grades were considerably stronger in Norway, Sweden, and the United States compared to Germany. This indicates that early tracking lowers children's chances to realize their potential for academic growth. Early tracking, therefore, seems to lead to untapped genetic potentials for education. This supports both theoretical perspectives: those that highlight quality differences in learning environments (enhancement mechanism) and those that argue that children in early tracking systems lack incentives to proof themselves (challenging mechanism).

In contrast to our expectations, genetic influences on educational achievement were similar in size in the United States compared to Norway and Sweden. This speaks against the claim that genetic influences on education are stronger in more open societies, as the United States has comparatively high levels of educational inequality (e.g. Grätz *et al.*, 2021). This finding may indicate that the institutional set-up of the educational system and longer periods of educational tracking are overall more relevant for genetic expression than the institutionalized social protection given that the United States and the Nordic countries are often considered to represent different ends of the welfare generosity spectrum (Esping-Andersen, 1990, 1999). However, this is certainly a preliminary conclusion and additional research based on larger country-samples is needed to back up this hypothesis.

This relates to a general limitation of our study as we miss a country that has an early tracking system and a liberal welfare regime. To our knowledge, such country context does not exist and we can therefore not assess the importance of the two institutional aspects in combination. Furthermore, while our comparative design enables us to assess whether the differences between single country cases are in line with our theoretical expectations about the macro-institutional features, the small-N design does not allow to quantify the impact thereof.

Relating our findings on cross-country differences in overall genetic influences on educational achievement to previous research on IQ and educational attainment reveals a striking pattern: in Germany, genetic influences on educational achievement are comparatively weak and shared environmental influences comparatively strong. This replicates previous results on genetic influences on educational attainment in Germany (Baier and Lang, 2019). In Sweden and the United States, by contrast, the findings of large genetic and mostly absent shared environmental influences on educational achievement are more similar to previous studies on adult cognitive ability (McGue *et al.*, 1993; Bouchard, 2009). Findings for Norway tend to follow this pattern while being less pronounced. Together, our findings suggest that genetic influences on educational achievement reflect those of cognitive ability more closely in comprehensive than in stratified schooling systems. Future studies are needed to analyse whether the overlap between genetic influences on educational achievement and cognitive ability differs systematically across educational systems, specifically, with the timing of tracking.

With respect to the social stratification of genetic influences, we do not find clear support in any of the countries besides Sweden. A possible explanation could be rooted in twins' age as twins in our study were at least 16 years of age or older. Similar to previous findings for cognitive abilities, the social stratification could be stronger for younger children—at earlier stages of their educational career—but become weaker and fade away during adolescence and young adulthood (Haworth *et al.*, 2010; Bouchard, 2013). In the context of life course variation it is also important to keep in mind that twins in our study are about 3 years older in the United States and Germany compared to twins from the Nordic countries. While we cannot rule out that genetic influences may be somewhat stronger in the United States and Germany as twins are older, we consider it—as discussed—as unlikely given the rather small age variation.

Differences between the two Scandinavian countries are unexpected given that Norway and Sweden are often considered similar in comparative research and have similar educational systems. This suggests that different mechanisms drive the intergenerational transmission of (dis-)advantage in these countries. In this respect, our study is in line with a recent comparison of sibling similarity across countries, which found the sibling similarity in education and their stratification to differ between Sweden and Norway (Grätz *et al.*, 2021). Together, these differences between Norway and Sweden demonstrate the limitations of broad country classification schemes typically used in macro-sociological comparative research (Esping-Andersen, 1990, 1999). While these classifications are conceptually useful, there is considerable empirical variety within the same welfare regime.

A possible explanation for support for the Saunders-hypothesis in Sweden but not in Norway could be rooted in the educational reforms that were implemented in the 1980s. While education in both countries experienced a period of decentralization and marketization, the shift to neo-liberal policies was more pronounced in Sweden, where the number of private schools increased and free school choice was introduced (Wiborg, 2013). Recent evidence shows that socioeconomically advantaged schools can protect students with lower PGS for education from dropping out of education (Trejo *et al.*, 2018; Harden *et al.*, 2020). This suggests that private schools in Sweden could represent an alternative strategy for advantaged parents to maintain their social advantage by selecting better schools for their children. Thus, a promising route for further research is to explore which institutional aspects account for the differences between Norway and Sweden.

In conclusion, our nationally comparative framework—combining comparative stratification and genetic research—indicates that early educational tracking operates as an environmental constraint for the development of genetic potential for education and opens up routes for further comparative research to better understand what kind of institutional settings shape the magnitude of genetic influences.

Supplementary Data

Supplementary data are available at *ESR* online.

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Tina Baier is a post-doctoral researcher at the University of Oslo. Her primary research interests include social inequality, education, family, and the integration of genetics in stratification research. Her work has been published in peer reviewed journals, such as *Journal of Marriage and Family*, *Sociological Science*, *European Sociological Review*, *Journal of Family Research*, and *Zeitschrift für Sociology und Sociopsychology*.

Volker Lang is post-doctoral researcher and lecturer in sociology at the University of Tübingen. His research interests comprise social inequalities of attitudes, survey experiments, and the social stratification of genetic influences. His recent research work has been published in *Sociological Methods and Research* and *Research in Social Stratification and Mobility*.

Michael Grätz is a researcher at the Institut des sciences sociales at the University of Lausanne and at the Swedish Institute for Social Research (SOFI) at Stockholm University. His research investigates the factors influencing the intergenerational transmission of advantage. He holds a PhD from the European University Institute in Florence, Italy.

Kieron J. Barclay is a Pro Futura Scientia Fellow at the Swedish Collegium for Advanced Study, an Associate Professor in Sociology at Stockholm University, and a Research Fellow at the Max Planck Institute for Demographic Research. His research is in the field of social demography and primarily concerns how family conditions are related to health and mortality, with a particular focus on the interrelationship between health and fertility. His work has been published in *Demography*, *Social Forces*, and *Population and Development Review*.

Dalton C. Conley is Henry Putnam University Professor of Sociology at Princeton University. He is also a Research Associate at the National Bureau of Economic Research and a Faculty Affiliate at the New York Genome Center. Among other topics, his research investigates the genetic and social transmission of health and socio-behavioural traits. He is an elected fellow of the National Academy of Sciences, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences.

Christopher T. Dawes is an associate professor in the Wilf Family Department of Politics at New York University. His research studies political behaviour with a focus on political participation and voter turnout. His work has appeared in journals, such as *Nature*, the *Proceedings of the National Academy of Sciences of the United States of America*, the *American Political Science Review*, the *American Journal of Political Science*, and *the Journal of Politics*.

Thomas Laidley is a post-doctoral fellow at the Institute of Behavioural Science and Institute for Behavioural Genetics at the University of Colorado, Boulder. He received his PhD from New York University in 2018, and some of his prior work can be seen in *Demography*, *Sociological Science*, and the *Proceedings of the National Academy of Sciences of the United States of America*, among others.

Torkild H. Lyngstad is professor of sociology at the Department of Sociology and Human Geography at the University of Oslo. His research is in the fields of demography, sociology, epidemiology, and criminology. His work has been published in *Demography*, *Journal of Marriage and the Family*, and *Population and Development Review*.