



Overriding Nature: Favourable Environments in Early Life Reduces Genetic Inequality in Political Participation

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Accepted: 14 October 2025
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Abstract

New research indicates that genetic variants related to educational attainment influence individuals' political participation. This suggests that political inequality of opportunity is partially rooted in an inequality in genetic resources. However, the possibility that these genetic influences are contingent on individuals' environments, such that they are amplified or reduced by certain environmental characteristics, remains unexplored. Using longitudinal and geo-coded register data for a large sample of genotyped twins in the Swedish Twin Registry, this paper explores whether early-life proximal environments that are conducive to participation modifies the effects of individuals' education-related genetic resources on voting, as measured by a polygenic index for educational attainment. The results suggest that the level of political engagement, and of SES, both within the family and within the neighbourhood, can reduce the effects of genetic resources on voting. This has implications for how we can direct policy to ameliorate genetic inequalities in political participation.

Keywords Political participation · Genetic resources · Polygenic index · Gene-environment interaction · Neighbourhoods · Equality of opportunity

Introduction

Explaining why some individuals participate politically, and why others abstain, constitutes one of the most important and extensively researched topics in all of political science. In particular, education has been widely recognized as a crucial resource that explains participation differentials (Verba and Nie 1972; Campbell et al. 1980; Brady

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et al. 1995; Verba et al. 1995; La Due Lake and Huckfeldt 1998; Hillygus 2005; Smets and van Ham 2013; Willeck and Mendelberg 2022). Traditionally, education has been seen as a *causal* predictor of political participation, providing citizens with knowledge and skills that reduce the costs of participating. However, and as discussed by Persson (2015), this traditional perspective has been challenged by those who argue that the effect of education reflects the relative influence of social status (Campbell 2009; Persson 2011), or, importantly, that the association between education and participation is explained to a significant degree by pre-existing individual-level factors (Kam and Palmer 2008; Mayer 2011; Dinesen et al. 2016; Ahlskog 2021).

One thought-provoking example of such a factor has turned out to be genetics. Twin studies suggest that substantial variation in both education (Silventoinen et al. 2020) and participation (Fowler et al. 2008) can be explained by genetic differences between individuals. Even more thought-provokingly, recent studies using molecular genetic data suggest that genetic propensities *for* educational attainment has a causal influence on voting (Dawes et al. 2021; Aarøe et al. 2021; Ahlskog et al. 2025). Beyond indicating that a non-negligible part of the education effect can be explained by genetics (Dinesen et al. 2016; Ahlskog 2021), this implies that inequality of opportunity (Verba et al. 1995) with regards to participation exists partially due to underlying inequalities in *genetic resources*.

At first glance, this might appear a troublesome proposition. How could we ever hope to fully reduce inequalities in participation, if they have their roots in something as fundamental as genetics? Crucially, though, genetic influence does not have to imply genetic determinism (Harden 2023). As one important example of non-determinism, genetic influences could vary depending on individuals' environmental circumstances. While there have previously been some attempts at uncovering *gene-environment interaction* with regards to participation (e.g. Boardman 2011), evidence is still vanishingly rare. In particular, there are no studies that exploit novel molecular genetics-based indicators of individual-level genetic propensities. The aim of this study is to reduce this research gap by examining which particular contexts matter for shaping the participatory effects of genetic resources, and, in turn, what could potentially be done on a policy level to reduce these genetic inequalities.

Specifically, this study investigates whether the effects of genetic propensities for education on voting depend on proximal social environments in early life. Whereas much attention in the participation literature has historically been devoted to individual-level factors (Smets and van Ham 2013), there is also an established tradition of viewing participation as a function of the social contexts in which individuals are embedded (Campbell 2013), including families (Beck and Jennings 1982; Verba et al. 1995; Plutzer 2002), as well as neighbourhoods (Huckfeldt 1979; Huckfeldt and Sprague 1993; Campbell 2009; Persson 2011; Bratsberg et al. 2021). Bringing these two classic perspectives on participation together, I explore the interaction between genetics and two particular environmental characteristics: the strength of *political engagement*, and the level of *socioeconomic status* (SES) in an individual's proximal social environment during early life.

The study is based on a large sample of genotyped twins in the *Swedish Twin Registry* (STR), which can be linked to validated turnout in a number of Swedish and European parliament elections, as well as uniquely fine-grained register data

on parent and neighbour characteristics. Regarding the latter, I make a particular contribution with the use of coordinate based, high-resolution *individualized* neighbourhoods. Following previous work, a *polygenic index* (EA PGI) is used to measure genetic propensities for educational attainment (cf. Dawes et al. 2021). To safeguard the analysis of genetic effects from common sources of confounding, the study leverages within-family variation in education-related genetics to identify the causal effect of genetic resources on voting, and then assesses whether this within-family effect differs depending on the proposed environmental characteristics.

The results indicate that education-related genetic resources have a weaker influence on participation within twin pairs who grew up in environments that were more conducive to participation. With regards to voting in national elections, family and neighbourhood political engagement as well as socioeconomic status (but family political engagement in particular) appear to reduce the within-family effect of the EA PGI. In fact, within the very highest levels of political engagement and SES, the within-family genetic effect cannot be distinguished from zero. These results mostly generalize to voting in second-order, European Parliament elections, although for this outcome the genetic effects tend to persist even under the most favourable circumstances. The results therefore suggest a compensatory interaction mechanism, where favourable environments reduce the role played by genetic resources. In extension, this indicates that the participatory inequality of opportunity that stems from genetic inequalities could be ameliorated by investing in socioeconomically disadvantaged families and neighbourhoods, as well as promoting political participation among adults, such that pro-participatory norms can be adopted by younger generations – thereby reducing the role played by genetics.

Theory and Previous Research

Having previously been regarded as a collection of exclusively 'social' outcomes (Hatemi and McDermott 2011), genetic perspectives on political behaviour would gain traction following the publication of a seminal study by Alford et al. (2005). Using a classic twin design, Alford et al. showed that latent genetic differences explain a substantial share of the variation in political attitudes. A steady stream of research followed in the article's footsteps, continuing the study of political attitudes and ideology, but also initiating a genetically informed discussion about the key outcome of political participation itself. The first twin study of voting (Fowler et al. 2008) found that genetic factors account for as much as half of the variation in voting in a sample of American twins (see also Boardman 2011). Similar findings would later be found in other populations (Klemmensen et al. 2012; Dawes et al. 2014). Although it had been proclaimed nearly a decade earlier that "all human behavioural traits are heritable" (Turkheimer 2000, p. 160), these studies left little doubt about the partially genetic etiology of participation.

It is only recently, however, that studies have begun illuminating *which* genetics were behind those heritability estimates. These studies rely on the novel research tool called *polygenic index* (PGI). A PGI is an individual-level variable that is based on molecular genetic data, and that summarizes an individual's overall genetic pro-

pensity for exhibiting a specific trait or outcome. Although studies based on PGI do not yet explain as much variation in participation as previous twin studies, they still suggest that genetics influence participation. In particular, it has been shown that a PGI which predicts an individual's education is causally associated with voting. This was first shown by Dawes et al. (2021) in a study of Swedish and American twins. As concluded by the authors, "inheriting genes beneficial for educational attainment makes individuals more likely to vote." (p. 5). Importantly, this study also indicates that educational attainment and cognitive ability mediates a significant part of the PGI effect. Similar types of findings were also found in a Danish study from the same year (Aarøe et al. 2021). Ahlskog et al. (2025), finally, extend these findings with regards to education-related genetics to include effects of PGIs for cognitive ability, depression, self-rated health and well-being. Of all PGIs studied to date, though, the one for education remains unequivocally the strongest genetic predictor of participation. With education ubiquitously being regarded as a key resource that shapes individuals' opportunities for participation, these findings suggest that inequalities in participation may partly have its roots in inequalities in *genetic resources*. Possessing these key genetic resources may be crucial in allowing an individual to easier acquire the cognitive but potentially also non-cognitive skills that increases his or her probability of participating as an adult (Dawes et al. 2021).

As already noted, the effect of these genetic resources on participation, just as any other complex social outcome, will be inherently distal and probabilistic (Madole and Harden 2022). As put by Ahlskog et al. (2025, p.2), genetic influences "do not at all imply a proximal biologically deterministic interpretation." One important way in which these effects could behave non-deterministically is by being environmentally dependent (Plomin et al. 1977), in a *gene-environment interaction* (GxE). The interest in GxE has been increasing quickly in the emerging social science genetics literature, following the increased adoption of PGIs. There are now numerous examples across different social science disciplines of how the effects of PGIs on various life outcomes, ranging from educational attainment and achievement to income, health and fertility, differ across various types of environmental characteristics (see Harden and Koellinger 2020; Mills and Tropf 2020; Dias Pereira et al. 2022; Benjamin et al. 2024; Biroli et al. 2025). Given the apparent ubiquitousness of GxE for other social outcomes, it seems plausible that genetic influences on participation could be moderated by the environment as well.

Any study of GxE needs to define its environment – in terms of content, but also in terms of scale. While the environment theoretically comprises anything that is external to the individual (Huckfeldt and Sprague 1993; Boardman et al. 2013), the focus here will be the individual's most proximal social context: the *family*, and the *neighbourhood*. The bulk of existing gene-environment interaction studies based on PGIs focus on different aspects of the family environment, whereas studies involving residential areas are still very rare (for exceptions, see Cheesman et al. 2022; Silva et al. 2025). In the political science literature, however, the notion that political participation is intrinsically tied to neighbourhood factors has deep roots (Huckfeldt 1979; Huckfeldt and Sprague 1993; Marschall 2004; Campbell 2006, 2013; Neundorf and Smets 2017). The idea that individual-level resources can interact with neighbourhood-level factors can also be found in the seminal work by Huckfeldt

(1979), where it is posited that high-resource environments can be particularly beneficial for the participation of high-resource individuals, while actually being detrimental for those low in resources.

Based on this discussion, it therefore seems appropriate to study whether the role of genetic resources are affected not only by family characteristics, but neighbourhood characteristics as well. Finally, since patterns of participation are commonly regarded as being shaped by early-life experiences (Plutzer 2002), and since the interaction between genes and environments is theorized to be most impactful during the formative years (Plomin et al. 1977; Bronfenbrenner and Ceci 1994; Shanahan and Hofer 2005), the study explicitly focuses on social contexts that are experienced during early life. Within families and neighbourhoods, the study will then examine two characteristics that appear *prima facie* relevant as moderators of the effects of genetic resources: the level of political engagement, and of SES (cf. Verba et al. 1995).

Political engagement here refers to behaviours and attitudes within an individual's social context that encourages him or her to participate. This could be acts of participation, such as voting, contacting politicians, signing petitions, and other forms of participation, or other manifestations of the importance of engagement with politics and societal issues. High political engagement could have important socializing effects during the formative years. According to Campbell (2013, p.43), it can instill the "cultural norm that good citizens are engaged in political life." Similarly, Huckfeldt (1979, p.580) notes the importance of "group based norms which turn participation into a social obligation." These norms could be instilled by parents (Beck and Jennings 1982; Plutzer 2002), as well as other individuals in the broader residential environment (Campbell 2006; Neundorf and Smets 2017). For recent empirical evidence to this effect, a study based on Norwegian register data shows that high turnout in exogenously assigned neighbourhoods increased residents' subsequent political participation (Bratsberg et al. 2021). Another study, based on Swedish register data, showed that adolescents' adult-life participation was increased by having a classmate whose parent was a politician (Aggeborn et al. 2020). In short, political engagement in the family as well as in the neighbourhood during early life may be crucial in providing individuals with pro-participatory norms that influence their subsequent participation (Neundorf and Smets 2017).

SES instead refers to the availability of socioeconomic resources within the individual's proximal environment. Most immediately, this includes the average level of education and income, but also each of the particular advantages that lie downstream from these factors, and that combine to create a socioeconomically enriched environment. At the family level, SES could be exemplified by parental investments in their child's skill and educational development (De Graaf et al. 2000; Cunha et al. 2006). In the neighbourhood, SES can proxy for access to well-functioning schools and other local institutions, as well as access to favourable peer groups and adult role models (Jencks and Mayer 1990; Brooks-Gunn et al. 1993). An abundance of socioeconomic resources, be that in the family or within the neighbourhood, can have positive effects on the development of cognitive as well as non-cognitive skills, or *human capital* (Heckman et al. 2006), which in turn can be instrumental in reducing the costs of participation. This effect could at least in part be mediated through education, as illustrated by studies finding associations between parental (e.g. Verba et al.

1995) and neighbourhood (e.g. Brooks-Gunn et al. 1993; Chetty et al. 2016) SES on education. While the bearing argument for political engagement was that it socializes individuals to participate via pro-participation norms, the argument for SES is rather that it provides individuals with the necessary skills. The evidence of contextual SES effects on adult-life participation is more mixed, at least as regards neighbourhood effects. Several studies find significant effects of parental SES on participation (Beck and Jennings 1982; Verba et al. 1995; Plutzer 2002; Quintelier and Hooghe 2013). Above-mentioned Huckfeldt (1979) also linked neighbourhood SES (measured in terms of average level of education) to higher political participation. However, a recent quasi-experimental study by Elder et al. (2023) finds no substantial effects of neighbourhood SES on participation (for similar findings, see also Bratsberg et al. 2021).

The key question in this study, however, is not whether contextual political engagement or SES have strong main effects on participation, but whether they moderate the relationship between genetic resources and participation. How might political engagement, for starters, affect this relationship? One plausible expectation is that high political engagement *decreases* the effects of genetic resources. In line with the GxE framework in Shanahan and Hofer (2005), individuals that are lacking in genetic resources may be particularly likely to benefit from strong participatory norms, thus receiving compensation from their surrounding environment. Conversely, individuals that are higher in genetic resources might be more likely to participate as a result of these participatory norms, rather than their genetic resources. In short, political engagement may provide a substitute for genetic resources. Another mechanism outlined in Shanahan and Hofer (2005) is *social control*: "social norms and structural constraints that are placed on people to limit their behavior and their choices" (p. 68). One could also conceptualize political engagement as a form of social control, or even as social pressure (Gerber et al. 2008), which reduces the amount of elbow room available for genetic resources to manifest themselves in relation to participation.

While this scenario appears intuitive, one should also consider the alternative: that political engagement enhances, or 'triggers' the effects of genetic resources. As argued by Boardman (2011, p. 199), we should expect genetics to be triggered in areas "with pro-participation norms and greater political activity." In this scenario, it is high-resource individuals that benefit disproportionately from a favourable environment. Interestingly, Boardman's twin analysis found some suggestive evidence that the heritability of voting was in fact higher for twins in US counties with higher levels of political engagement. Instead of being a substitute, this would make political engagement a *complement* to genetic resources.

This kind of enhancement mechanism also appears especially plausible when it comes an interaction with SES. In the social science genetics literature, it is commonly hypothesized that an abundance of socioeconomic resources increases the expression of genetics for positive traits and life outcomes. Where socioeconomic resources are lacking, genetic expression will instead be constrained (see e.g. Papageorge and Thom 2020). This idea has its roots in the so-called Scarr-Rowe hypothesis, which posits that the heritability of cognitive ability is larger for individuals from high-SES families (e.g. Turkheimer et al. 2003). Recently, the Scarr-Rowe hypothesis has been applied to educational outcomes (Ghirardi et al. 2024). If high SES was to enhance

the expression of genetics associated with cognitive skills and education – the two key mediators of the effect of an EA PGI on voting (Dawes et al. 2021) – this could cause genetic resources to become even more predictive of participation, by further lowering skill-related barriers to participation. Evidence of enhancement has been shown in recent studies of how effects of education-related genetics on educational and economic outcomes are increased by family-level SES (e.g. Papageorge and Thom 2020; Ronda et al. 2022), as well as school-level SES (Trejo et al. 2018). An interesting parallel here is the older finding by Huckfeldt (1979) that the association between neighbourhood-level education and individual-level participation is larger for highly educated individuals. While Huckfeldt understandably does not include genetics in his framework, this essentially refers to the same kind of complementary relationship between individual and contextual resources.

At the same time, there are also GxE studies that suggest that SES decreases the effects of genetic resources (Harden et al. 2020; Cheesman et al. 2022; Silva et al. 2025). It could be that access to socioeconomic resources serves to equip individuals – especially those low in genetic resources – with the necessary skills and human capital, thus reducing the role played by genetics. The end-result would be the same as in the interaction with neighbourhood political engagement, but the mechanism would rather be the compensation of skills rather than norms that limit the role of genetics. Relatedly, but running counter to Huckfeldt (1979), Campbell (2009) and Persson (2011) find evidence of a *negative* interaction between individual-level education and the contextual level of education.

The paucity of research regarding interactions between genes and social contexts in the context of political participation makes it difficult to make any strong predictions as to what type of interaction will be uncovered. Ultimately, the question of whether and how the effects of genetic resources depend on these environmental characteristics is an empirical one.

Case, Data and Empirical Design

The context for the study is Sweden, a well-functioning parliamentary democracy with a high level of turnout. More specifically, the study is based on a sample of approximately 10 000 genotyped, fraternal twins in full sibling pairs in STR, born 1960–2004. As explained below, studying fraternal siblings, who share on average fifty percent of their genes, is crucial for identifying causal effects of PGI. Using pseudonymized personal identifiers, these twins can be linked to high-quality register data, made available for research by Statistics Sweden. These data are used to obtain the twins' validated turnout in a number of elections, as well as exceptionally rich information about their parental and neighbour characteristics during their early years.

With the exception of the algorithm used in the process of creating measures of neighbourhood characteristics (see below), all analyses were performed in Stata. For an ethics approval statement, and for information about accessing the relevant data and scripts used to produce the analyses, see Online Appendix section 1.

Measuring Political Participation Using Validated Turnout Data from Swedish Registers

The dependent variable that will be used throughout is *voting* in percentage points, and more specifically each twin's life-time average turnout in the elections available for that twin. In focus here is voting in Swedish national elections, and in European Parliament (EP) elections. Thanks to the digitization of publicly available election rolls (for further information, see Lindgren and Oskarsson 2023), validated information on turnout in national elections are available in the registers for 1994, 2010, 2018, and 2022. For EP elections, information is available in 2009 and 2019. In 1994, there were two national elections, one for the parliament, and the referendum regarding Sweden joining the EU. I include the referendum in order to increase the number of data points. With the Swedish minimum voting age being 18, the latest-born twins to be included in the analyses are born in 2004, and 2001, respectively. It follows from this approach that the number of data points per cohort will differ. The participation of the very youngest cohorts will equal their participation in one single election, whereas that of the older cohorts will be the average across several elections. This approach is in line with a recent study by Lindgren and Oskarsson (2023), also based on Swedish register data.

Although the EU plays a significant role for Sweden and for Swedish politics, EP elections are generally regarded with relatively low interest by Swedish citizens. They receive less public attention and engagement, embodied by a consistently and significantly lower turnout than in national elections (see Table 1). Representing first-order and second-order elections, the results for the national and EP voting outcomes are presented separately.

Measuring Genetic Resources Using Molecular-genetic Data

The key independent variable, and that measures each twin's genetic resources, is a polygenic index for educational attainment (EA PGI). The EA PGI is an individual-level predictor of educational attainment in adulthood, whose predictive ability comes from aggregating information about a vast number of genetic variants, scattered across the human genome, that have previously been shown to be statistically associated with education. These genetic variants are called single-nucleotide polymorphisms (SNP). SNPs are locations in the DNA sequence where individuals vary with regards to single DNA bases (adenine, thymine, cytosine, and guanine). By summing up the effect sizes of each education-related SNP possessed by an individual, multiplied by the number of copies of each SNP, an EA PGI can be constructed for anyone, provided he or she has been genotyped.

The EA PGI used for the twins in this study is based on the approximately 1300 SNPs that were discovered in the third GWAS for educational attainment (Lee et al. 2018). Based on those SNPs, PGI values have then been constructed for each STR twin following the procedures outlined in the Polygenic Index Repository (Becker et al. 2021). Notably, the used PGI is a *multi-trait* EA PGI. A multi-trait PGI leverages the genetic correlation between the target trait (in this case educational attainment) and other related traits in order to enhance the prediction of the target trait

Table 1 Descriptive statistics

Variables	(1)	(2)	(3)	(4)	(5)
	N	mean	sd	min	max
a) National					
Vote (national)	10,480	91.65	22.97	0	100
EA PGI	10,480	-8.93e-06	0.996	-3.688	3.633
Neighbourhood SES	10,480	2.983	1.343	1	5
Neighbourhood vote	10,480	2.989	1.414	1	5
Parent SES	10,480	2.836	1.189	1	5
Parent vote	10,480	3.560	1.432	1	5
Neighbourhood population	10,480	174.2	212.7	50	2,327
Birth year	10,480	1,991	11.67	1,960	2,004
Sex (woman)	10,480	0.521	0.500	0	1
b) EP					
Vote (EP)	8,554	59.11	46.25	0	100
EA PGI	8,554	-0.000665	0.996	-3.688	3.633
Neighbourhood SES	8,554	2.982	1.341	1	5
Neighbourhood vote	8,554	2.992	1.410	1	5
Parent SES	8,554	2.843	1.198	1	5
Parent vote	8,554	3.523	1.408	1	5
Neighbourhood population	8,554	174.2	212.0	50	2,327
Birth year	8,554	1,989	11.57	1,960	2,001
Sex (woman)	8,554	0.527	0.499	0	1

The sample(s) only contains twins with their sibling in the data, and that are non-missing on all the used variables

(Turley et al. 2018; Becker et al. 2021). Multi-trait PGI prediction is expected to outperform single-trait prediction, as shown by Turley et al. (2018). Additionally, cognitive ability is one of the supplementary traits used to create this multi-trait PGI, which should make it appropriate as a comprehensive measure of the twins' genetic resources.

Prior to inclusion, the PGI was standardized within birth cohort and genotyping batch. When included in a regression, the beta coefficient for the PGI shows the degree to which a standard deviation increase in the PGI from the sample mean (relative to birth year and batch) is associated with a one percentage unit increase in voting. Robustness tests will include analyses using the corresponding single-trait PGIs for education and cognitive ability, and the single-trait version of the most recent EA PGI, based on a GWAS of about 3 million individuals (Okbay et al. 2022). For an extended discussion about the theoretical and methodological rationales behind the use of GWAS and PGI, as well as a motivation for using a multi-trait PGI, see section 2 in the Online Appendix.

Measuring Proximal Environments Using Multi-generational and Geo-coded Register Data

To measure the twins' environmental characteristics in early life, I exploit parental and geographical identifiers within the STR-linked register data. For additional details regarding the underlying data sources, see Online Appendix section 3.

To measure political engagement, I use the level of voting on the part of parents and neighbours, respectively. While it would have been advantageous to also have measures on participation-related attitudes and norms – based on survey data, for instance – such data are not available. Still, the level of voting should represent a feasible indicator of the strength of political engagement within the twins' proximal environment. Parent and neighbourhood voting was measured using the same approach as for the twins' own voting, i.e. using their life-time average turnout in available elections (here also including the national election in 1970 if applicable). The rationale for measuring the life-time average turnout rather than turnout in specific elections during the twins' formative years is that this is more likely to capture a latent propensity of these individuals to participate, which may be more relevant than if they voted in one particular, time-adjacent election. Additionally, the number of elections in the data is very small, as is the overall variation in turnout, especially among parents.

SES is measured using a combination of three commonly used indicators: education years, income, and occupational prestige. These have previously been referred to as the 'big three' with regards to capturing SES (Lindgren et al. 2019), and can be measured relatively consistently over time using information in older censuses and more recent administrative registers. Education years is based on Swedish educational codes (for conversion, see Table A1). Income is captured using annual work income. Occupational prestige, finally, is captured using occupational codes that have been mapped to the occupational prestige scale developed by Treiman (1976, see conversion in Table A2). Each of the SES variables, on the parental and neighbourhood level, were transformed into quintiles within twin birth year in order to account for scale differences and cohort differences, and then an average was taken across the three quintile-transformed variables to construct a final SES index. To simplify comparisons between SES and political engagement, parental and neighbourhood voting were also transformed into quintiles.

To connect the twins to their parents, I exploit parental identifiers contained in the Multi-Generation Registry. To capture each indicator on the parental level – voting, and the three socioeconomic variables – a dominance principle was applied, so that the highest value between the parents is used. This allows for one parent to be missing on the variable in question, thus minimizing missing observations. Parental voting, for example, equals the highest-participating parent's life-time average turnout. Parental education, income, and occupational prestige were measured in the year when the twin was 15, or as close as possible (the exact age at measurement varies depending on data availability over time; see table A7).

To measure the twins' neighbourhood characteristics in early life, I create so-called *individualized* neighbourhoods – neighbourhoods that are based on geographically proximal individuals, rather than administrative boundaries (cf. Andersson and

Malmberg 2015). Using individualized neighbourhoods presents a partial solution to the Modifiable Area Unit Problem (MAUP), which says essentially that analyses based on administratively defined neighbourhoods will be prone to measurement error and low reliability (Andersson and Malmberg 2015).

The individualized neighbourhoods were created using an original nearest-neighbours algorithm developed by Ahlskog (2025)¹, which exploits residential coordinates corresponding to 250x250 meter square grids (in some rural areas, 1000x1000 meter squares were used), contained in the Total Population Register. For the purpose of this study, the algorithm combines geographical coordinates for the STR twins with those of adult individuals (age 20 and above) in the full Swedish population. Using the full-population register data, the algorithm first incrementally identified the 'neighbours' of each center coordinate in the data, using a maximum search range of 5000m, searching for a minimum of 50 neighbours.² Among each set of neighbours were then calculated the averages of (life-time average) voter turnout and SES in each available year. These neighbourhood averages, plus neighbourhood population counts, were then mapped onto the STR twins, matching on their residential coordinates when they were 15 (cf. Brandén et al. 2023). Residential coordinates are available in the registers from 1982 and onward, meaning that the 1967 cohort was the first that could be assigned their individualized neighbourhood at exactly age 15. To increase the sample, I also include the 1960-1966 cohorts, using the neighbourhood of their mothers (or fathers, if missing) in 1982. To get a reference of the fine-grainedness of these neighbourhoods, the average number of neighbours is approximately 174 (Table 1). The distribution of these neighbourhood population counts can be seen in Figure 1.

Exploiting Within-family Genetic Differences in the Study of GxE

Although individuals' genetics are fixed at conception, there are nevertheless some important challenges with regards to identifying causal effects of PGIs. The predominant challenges are *population stratification*, *genetic nurture*, and *assortative mating*. Population stratification refers to the fact that differences in genetic ancestry between populations or subpopulations that arise due to non-random mating across geographic or social barriers can give rise to spurious genetic associations when coupled with environmental differences (Price et al. 2010; Young et al. 2019). Genetic nurture refers to how an individual's outcome can be affected by the genetics of parents and other more distant relatives via environmental pathways (Kong et al. 2018; Wang et al. 2021; Nivard et al. 2024), leading the PGI to also capture indirect genetic effects of relatives. Assortative mating, finally, refers to the existence of non-random mating among biological relatives, most immediately parents, on the outcome in question, or a correlated outcome. Assortative mating causes genetic variants that are included in the PGI to be correlated with other outcome-related genetic variants in a way that

¹For more information, see <https://github.com/RafaelAhlskog/LC>.

²Although 50 was chosen as the preferred number of neighbours, in densely populated areas the search will exceed 50 neighbours already within the first search layer.

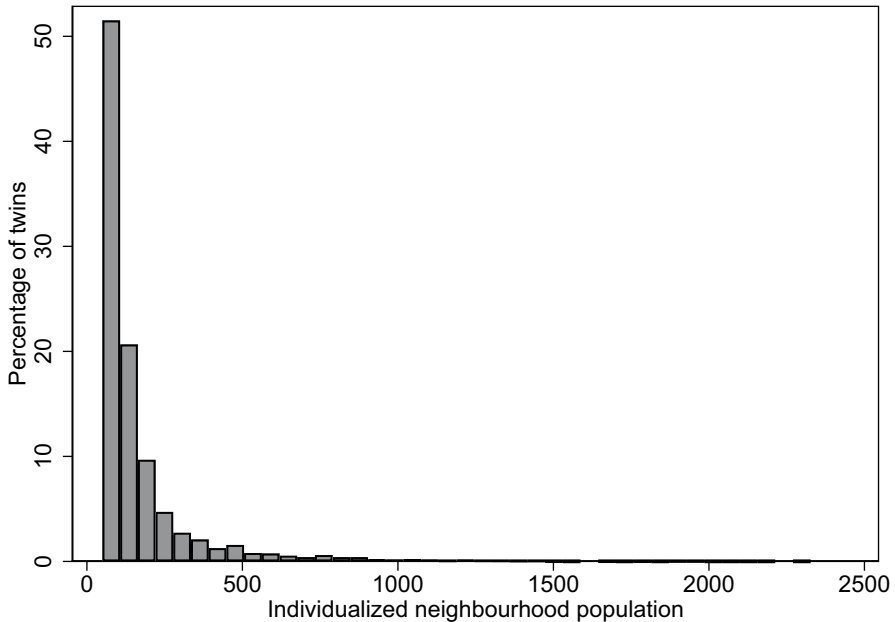


Fig. 1 Distribution of individualized neighbourhood populations

they would not be under random mating, so that the PGI effect becomes inflated (Young et al. 2019; Okbay et al. 2022).

Fortunately, these challenges can be effectively met by studying the effects of PGI differences between biological siblings, like dizygotic twins. Following Mendel's law of random segregation, genetic differences between siblings are completely random (Madole and Harden 2022), and will not be subject to the confounders outlined above. The importance of within-family designs in studies of PGI has been strongly emphasized in recent work (e.g. Selzam et al. 2019; Madole and Harden 2022; Cheesman et al. 2023), and has been described as the “gold standard to correct for confounds in genetic association studies” (Harden and Koellinger 2020, p. 569). In this particular context, it allows for the effect of the EA PGI on voting to be causally identified (cf. Dawes et al. 2021; Ahlskog et al. 2025). Studying twins as opposed to normal siblings, as is the case here, also carries the advantage of eliminating any potential influences related to age, cohort, or birth order differences that might otherwise distort an analysis of GxE.

Nevertheless, the within-family PGI effect is expected to be significantly attenuated, partly because it will more closely resemble the unconfounded PGI effect, but also because there will be lower variation both in genetics and in the outcome between siblings than between unrelated individuals. Additionally, using a PGI that is based on a between-family GWAS in a within-family analysis is likely to introduce additional measurement error (Trejo and Domingue 2018). An attenuated main effect will make it harder to detect GxE, as will also the fact that the GWAS on which the PGI is based consists of individuals from a variety of environments. This means that the SNPs that manage to shine through this environmental 'noise' will likely

tend to be those that are stable across environments (Harden and Koellinger 2020; Domingue et al. 2020). In short, there are several reasons to expect findings of GxE to be conservatively estimated.

Exploiting EA PGI differences within families, then, allows us to study the causal effects of genetic resources, which is equivalent to controlling for twin-pair fixed effects. To then assess whether these within-family effects are environmentally moderated, we can interact the within-family PGI differences with *between-family* variation in the environmental characteristics. Are higher levels of political engagement or SES associated with lower or higher genetic effects within families? If genetic effects become lower, this suggests compensation. If they become higher, it instead suggests enhancement, or triggering.

While this study accomplishes a robust identification of the genetic effect, we need to interpret the moderating effect of the parental and neighbourhood variables more cautiously. We cannot rule out the possibility that the environmental characteristics are actually capturing something else, and that we cannot measure in this particular case. For example, an interaction between genes and parent or neighbour SES could partially be capturing an interaction with individuals' SES-related genes – a gene-gene interaction (cf. Conley 2025). Similarly, an interaction with neighbourhood political engagement might capture an interaction with neighbours' genetically conditioned personality traits. Most pressingly, though, we need to assess whether the interaction with parental SES or political engagement is not in fact capturing the interaction with their neighbourhood equivalents, and vice versa. While we need to remain humble regarding the de facto content of the moderator, we should not have to worry about issues relating to reverse causation or self-selection. The twins cannot select their parents, nor (at least during the early years) their neighbours (cf. Ahlskog 2024). To err on the side of caution, the models will include interactions with the family mean EA PGI, as well as family mean EA PGI squared in order to account for potential non-linearities.

Below are the empirical models that will be estimated. First is a baseline model that estimates the average, within-family EA PGI effect on voting:

$$\Delta Vote_j = \beta_0 + \beta_1 \Delta PGI_j + \Lambda_j + \epsilon_j \quad (1)$$

where, notably, the unit of analysis is fraternal twin pair j . $\Delta Vote_j$ is the sibling difference in voting within each twin pair. ΔPGI_j is the sibling difference in the EA PGI. Λ_j includes controls for potential sex difference within a twin pair, genotyping batch³, twin-pair average EA PGI, and twin-pair average EA PGI squared.

Second is the key GxE model that estimates the degree to which the within-family EA PGI effect changes depending on contextual voting and SES, measured between families:

$$\Delta Vote_j = \beta_0 + \beta_1 (\Delta PGI_j \times P_j) + \beta_2 (\Delta PGI_j \times N_j) + \Omega_j + \epsilon_j \quad (2)$$

³ STR was genotyped in three different batches, using different genotyping arrays. The quality with which SNPs are imputed might differ across the genotyping arrays, meaning that the predictive power of the PGI may differ systematically between batches. Hence, these batches need to be included as controls.

where $\Delta PGI_j \times P_j$ and $\Delta PGI_j \times N_j$ capture the interactions between the EA PGI and each environmental characteristic, on the parental and neighbourhood level, respectively. Ω_j includes the individual terms of the interactions, neighbourhood population size, the controls in Eq. 1, as well as the interactions between each variable in the model, including between each covariate (Keller 2014).

Descriptive statistics, containing the final sample size for each voting outcome, and summaries for all the key variables in the main analyses, can be seen in Table 1.

Results

The key results of the study are contained in Figure 2, which plots the estimates from a series of regression models, the exact estimates for which can also be seen in Table 2. Worth noting in relation to these regressions is that the *main* effects of the environmental variables are not included, since they have no meaningful interpretation; they would in effect capture the effect of the environment on within-family differences in voting. What is crucial in these analyses is whether the within-family effect of the EA PGI differs depending on the values of these variables.

We can begin by confirming that there is an average, within-family effect of the EA PGI on voting: approximately 2 percentage points per standard deviation with regards to national elections, and 5 pp with regards to EP voting. This difference is not unexpected, in that the variation for voting in EP elections is much larger than for national voting (cf. Dawes et al. 2021).⁴ In short, genetic resources are associated with voting. Importantly, though, we also see evidence of GxE. Beginning with the results for national voting, there are clear indications that both higher political engagement and SES are associated with a *decrease* in the PGI effect. Looking at models 2 through 4, we see negative interactions with both parental voting and neighbourhood voting – though especially with parental voting, with an interaction coefficient of nearly 1 percentage point per parental voting quintile ($p=0.010$). The interaction with neighbourhood voting is approximately half a percentage point per quintile ($p=0.071$), which is still sizeable compared to the main effect of the PGI. The interactions are weakened slightly when both terms are included together in the same model, and the interaction with neighbourhood voting falls short of reaching $p<0.1$ ($p=0.168$). Looking at models 5 through 7, the interactions with parental and neighbourhood SES are quite similar in magnitude. The interaction with parental SES is nearly as large as the interaction with parental voting ($p=0.041$), and the interaction with neighbourhood SES is slightly larger than for neighbourhood voting ($p=0.039$). In model 7, the interactions are weakened somewhat, however, and fall short of reaching $p<0.05$ (parent SES: $p=0.170$; neighborhood SES: $p=0.181$).

⁴As can be seen in Table 2, the R^2 is quite low; lower than 1 percent in the case of national voting, and slightly over 1 percent in the case of EP voting. It is important to remember that the outcome that the EA PGI originally predicts is educational attainment, and not voting. Moreover, the variance in educational attainment explained by the EA PGI is limited in comparison with the heritability estimates obtained in classical twin studies (see Lee et al. 2018). Finally, as noted in the methods section, the effect is also expected to be attenuated when estimated between siblings. The low R^2 is therefore not unexpected, and may increase in the future as more powerful PGIs are made available.

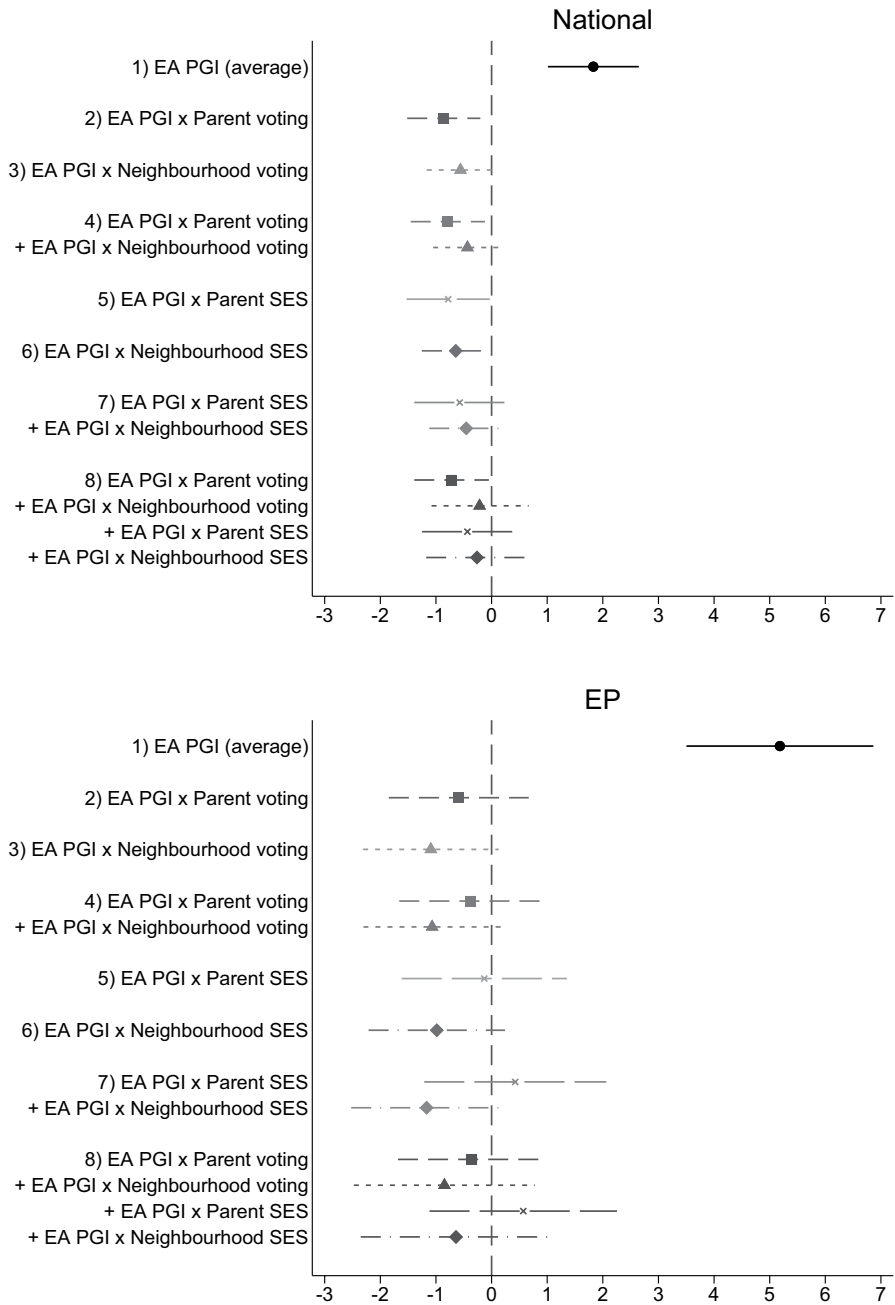


Fig. 2 Results from gene-environment interaction models. Note: Estimates are shown with 95 percent confidence intervals. Color shades correspond to models. Marker symbols correspond to variables and interaction terms

Table 2 Results from gene-environment interaction models

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
a) National								
Δ EA PGI	1.830*** (0.417)	5.321*** (1.566)	4.021*** (1.305)	6.451*** (1.800)	4.365*** (1.335)	4.133*** (1.242)	5.132*** (1.465)	7.453*** (1.924)
Δ EA PGI \times Parent voting		-0.859** (0.336)		-0.787** (0.341)				-0.719** (0.342)
Δ EA PGI \times Neighbour- hood voting			-0.559* (0.310)	-0.433 (0.315)				-0.215 (0.441)
Δ EA PGI \times Parent SES					-0.780** (0.382)		-0.572 (0.417)	-0.413 (0.415)
Δ EA PGI \times Neighbour- hood SES						-0.644** (0.312)	-0.455 (0.340)	-0.262 (0.466)
Constant	1.272* (0.678)	4.362* (2.358)	1.695 (1.809)	1.752 (3.853)	3.775* (1.961)	3.371* (1.819)	5.906* (3.407)	10.699* (5.661)
Observations	5,240	5,240	5,240	5,240	5,240	5,240	5,240	5,240
R-squared	0.005	0.012	0.011	0.014	0.011	0.011	0.012	0.019
b) EP								
Δ EA PGI	5.184*** (0.857)	7.731*** (2.694)	8.958*** (2.399)	10.281*** (3.141)	6.036** (2.564)	8.427*** (2.255)	7.836*** (2.718)	9.793*** (3.324)
Δ EA PGI \times Parent voting		-0.590 (0.641)		-0.378 (0.654)				-0.352 (0.678)
Δ EA PGI \times Neighbour- hood voting			-1.091* (0.621)	-1.068* (0.631)				-0.848 (0.831)
Δ EA PGI \times Parent SES					-0.131 (0.758)		0.426 (0.835)	0.578 (0.859)
Δ EA PGI \times Neighbour- hood SES						-0.984 (0.626)	-1.167* (0.692)	-0.640 (0.874)
Constant	-0.833 (1.302)	-5.075 (3.684)	1.240 (3.338)	-4.014 (6.209)	3.073 (3.635)	-0.748 (3.249)	-0.819 (5.895)	-4.126 (8.635)
Observations	4,277	4,277	4,277	4,277	4,277	4,277	4,277	4,277
R-squared	0.012	0.016	0.018	0.019	0.016	0.016	0.017	0.021

Standard errors within parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Model 8 presents each parental and neighbourhood interaction when included in the same model. These results are important, in that they may indicate whether each of the environmental characteristics are consequential independently of one another. Estimating this joint model weakens most of the interaction terms; only the interaction with parental voting is retained in terms of size and statistical significance ($p=0.035$). However, these patterns are arguably not unexpected, considering that these contextual variables are non-negligibly correlated with each other, especially the neighbourhood-level variables (see Table A8). It is therefore not unlikely that these weaker and noisier interactions are due to having introduced multicollinearity into the model.⁵ In other words, while model 8 appears to provide consistent evidence only for an interaction with parental political engagement, it may also be providing an overly conservative picture of the patterns of interaction between the EA PGI and the environmental characteristics overall.

The interactions with regards to EP voting are generally similar in size, but are less precisely estimated. This is perhaps surprising given the larger variation in the outcome variable, and the larger average effect of the PGI. However, these results are based on about 2000 fewer twins, which is a significant drop in sample size. These noisier estimates could therefore simply be a consequence of reduced statistical power. One potential discrepancy of note is that neighbourhood voting comes out as a stronger and more consistent moderator than parental voting, for which the interaction cannot clearly be distinguished from zero. It should be said, however, that these discrepancies are all within the margin of error for each interaction, making it hazardous to draw any strong conclusions. We also see indications that, while neighbourhood SES continues to have a negative impact on the EA PGI effect (and potentially more so here than for national voting), the interaction with parental SES is zero, and even positively signed in models 7 and 8. Given the large confidence bands, though, it is not obvious whether to actually treat this as an instance of enhancement. Overall, the neighbourhood-level characteristics appear to be more consequential than family-level characteristics in terms of moderating the genetic effect on voting in second-order, EP elections.

In sum, these main results point in the direction of a compensatory interaction between genetic resources and the proximal environment: the within-family effect of the EA PGI tends to become lower, as parental and neighbourhood voting or SES gets higher. Parental voting comes out as the most consistent moderator with regards to national voting, but, as discussed, it is not unlikely that the other factors may have an impact as well. The results for EP voting, while being less precise, also suggest compensation, with the exception for parental SES. A potentially interesting discrepancy between first-order and second-order elections is that neighbourhood characteristics came out as stronger moderators of the genetic effect on EP voting, compared to parental characteristics for national voting.

⁵ One way to assess the pervasiveness of multicollinearity is to compare the average variance inflation factor (VIF) between the models. Whereas models 2-7 in the present case reach VIFs well below 10, which is commonly used as a rule of thumb, model 8 has an average VIF of nearly 14 (exact figures available on request).

Additional Analyses

The main results illustrate the moderating impact of both parental and neighbourhood factors – with the analyses of the latter having been possible through the use of individualized neighbourhoods. These neighbourhoods were based on a search for the twins' closest 50 neighbours, although in practice, a majority of the neighbourhoods were more populated than that (see Figure 1). It is plausible that the impact of the neighbourhood is larger the more proximal it gets. Hence, it is worthwhile testing whether the results change when excluding the twins in the very largest neighbourhoods. Figure A1 shows the equivalent plots, having dropped twins in neighbourhoods with a population of 200 and above. The patterns are mostly in line with the main results; one potentially interesting difference is that the compensatory impact of neighbourhood political engagement is reduced, whereas that for SES is increased. Though these changes are well within the margin of error, this could potentially mean that socioeconomic resources within the most proximal residential area is more consequential than political engagement.

We have thus far assumed that the interactions between the PGI and the environmental variables are linear in nature. As a way of scrutinizing this assumption, Figure 3 shows rolling regressions of the voting outcomes on the EA PGI, within each quintile of the parent and neighbourhood indicators, using the same set of controls as in the baseline model (Eq. 1).⁶ The plots generally suggest that the PGI effect decreases approximately linearly across levels of the environmental variables, and in the case of national voting, interestingly, to the point where it cannot safely be distinguished from zero. In other words, we cannot say with statistical certainty that the EA PGI actually has an effect on voting among individuals from the most favourable contexts. Looking at EP voting, we also find a potential explanation for the null or slightly positive interaction with parental SES. The interaction is not clearly linear, but we can still observe the PGI effect decreasing, nearing zero in the very highest quintile. In other words, upon closer inspection, the interaction with parental SES appears to point in a negative direction also in the case of EP voting.

In some further analyses, the multi-trait PGI for educational attainment is substituted with the single-trait PGI for educational attainment and for cognitive skills (Figure A2-A3). The same patterns are obtained, albeit with less precision than in the main analyses, which is not unexpected considering the lower predictive power of these PGI, especially that for cognitive skills. Using the more recent EA PGI based on Okbay et al. (2022), similar although not equally precise results are also obtained (Figure A4). While it might seem surprising that this later iteration of the EA PGI does not perform as well as the one used in the main analysis, this newer PGI remains a single-trait PGI, as opposed to a multi-trait PGI. The resulting difference in baseline predictive power will inevitably affect the power to detect gene-environment interaction.

Figure A5 contains the interactions with parental and neighbourhood SES, broken down into its three components: education, income, and occupational prestige. These analyses do not reveal any radical differences between the SES components, although

⁶The rolling regressions are plotted using a Gaussian kernel function with a bandwidth of 1.

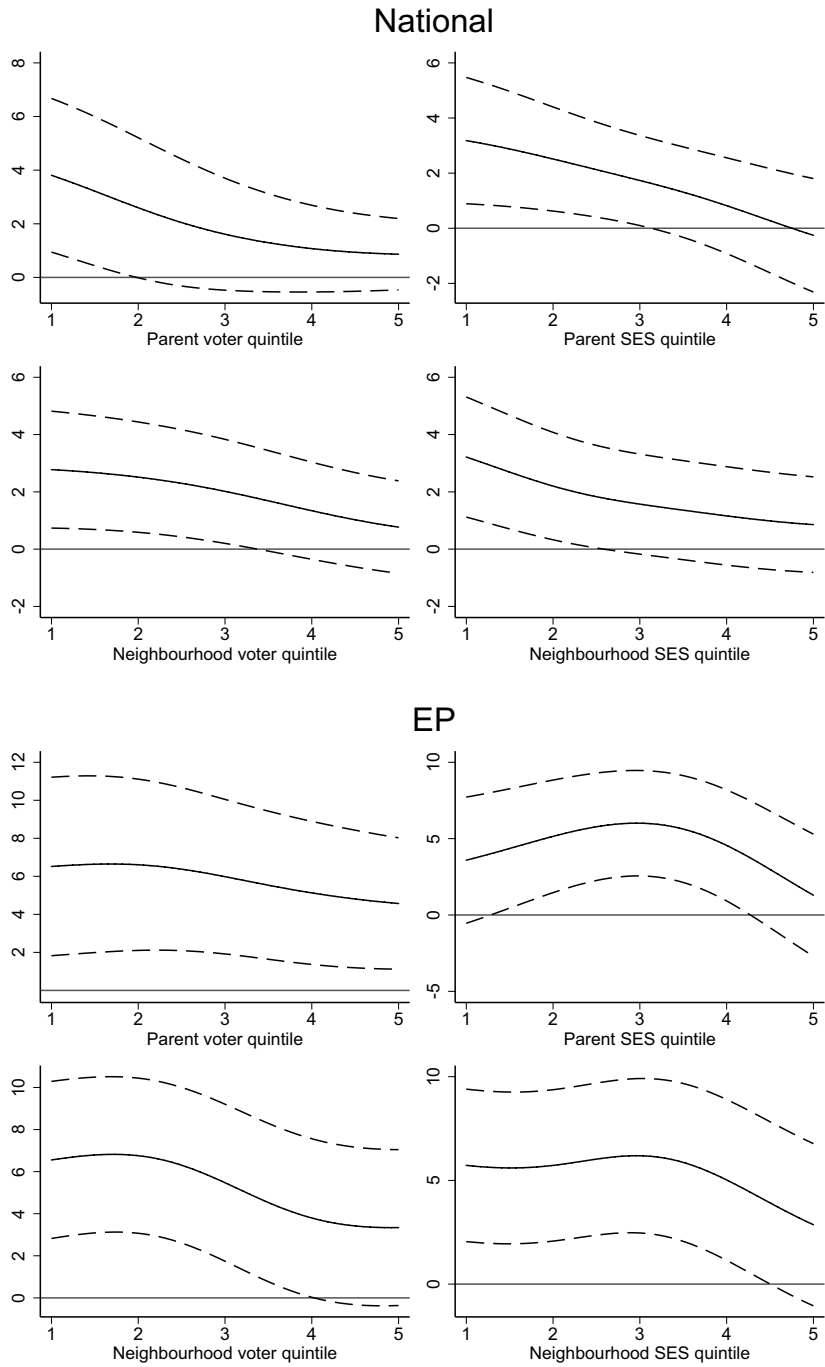


Fig. 3 Rolling regressions of EA PGI across quintiles of parent and neighbourhood variables

education, surprisingly, does not appear to be the most important moderator. On the parental level, the interaction with occupational prestige is actually the most sizeable, although comparable in magnitude to the other two components. A possible explanation for this is that the variation in education is limited among parents, compared to the other SES indicators. On the neighbourhood level, the interactions are of similar magnitude.

It has been noted in the methodological literature concerning GxE that a range-restricted dependent variable could cause spurious patterns of interaction, if the mean of the dependent variable increases as the levels of the moderator gets higher (Domingue et al. 2020). In this case, the amount of variation left in voting for the EA PGI to explain might become mechanically reduced, which would show up as a negatively signed interaction. This risk appears to be highest for national voting, with a sample mean of nearly 92 percent, compared to 59 percent for EP voting (see Table 1). Figure A6 also indicates that the means of both outcomes increase given higher values in the moderators. One way to probe for this kind of ceiling effect is to employ ordered logistic regression models; when interpreted on the untransformed log odds scale, the beta coefficient of the interaction should be independent from the mean in the outcome (cf. Pettersson 2025). Figure A7 and Table A13 contains the main results based on such ordered logit models. The patterns are very similar to those based on OLS. While we cannot, of course, fully rule out the possibility of ceiling effects influencing the results, these analyses do at least not suggest this to be particularly pervasive.

Table A14 contains a further robustness test, which assesses whether the within-family EA PGI effect differs systematically depending on between-family differences in genetic ancestry, as measured by a set of principal components (PC) of the underlying genetic data. Within the STR sample, exploiting between-family differences in PCs represents a way to capture how genetic differences cluster geographically across Sweden.⁷ This type of genetic clustering could potentially be related to the environmental characteristics under study. Might the environmental variables simply mirror geography, rather than the qualitative characteristics themselves? The regressions do not provide any systematic indications of interactions between the within-family PGI and the first ten, family-averaged PCs, having included the same set of basic controls as in Eq. 1. This suggests that the environmental characteristics under study capture something substantively important, at least beyond geographically driven differences in genetic ancestry.

Finally, it was noted earlier that using pre-defined residential areas as approximations of neighbourhoods comes with various methodological issues. Nevertheless, they may prove useful as a replication exercise. Besides residential coordinates, the Swedish registers also contain annual information about parish of residence. Parishes are legacy administrative areas, being originally used by the state and the church to "collect taxes and enrol soldiers" (Ludvigsson et al. 2016, p. 126). The parishes are larger and more highly populated than our previously used individualized neighbourhoods (see Figure A9), but whereas we could only create individualized neighbourhoods from 1982 and onward, parish contexts can be measured as early as 1960.

⁷For graphical illustrations of how the first three PCs cluster across Sweden, see figure A8.

Parishes can therefore be linked to twins born as early as 1940, providing a sizeable sample increase of about 4000 twins in full sibling pairs (see Table A15, including additional descriptive statistics).⁸

Figure 4 contains the results based on the parishes (for exact estimates, see Table A16). Beginning with national voting, the interactions appear to be somewhat smaller overall, but, thanks to the larger sample size, more precisely estimated. In the main analyses of national voting, it was mainly the interaction with parental voting that was stable when included together with the other contextual variables. Here we see further indications that the interactions with neighbourhood voting and SES, and parental SES as well, also remain even in the final, joint model. Each interaction is actually of very similar size, even in model 8. For EP voting, the results are also similar, with the exception that parish voting does not appear to decrease the EA PGI effect as clearly as it did in the main analysis. Parish SES, instead, comes out as the stronger moderator, decreasing the EA PGI effect on voting in EP elections by more than 1 percentage point per quintile. The indications of a positive interaction with parental SES can also be found here, but as we saw earlier, this is likely masking a non-linear pattern. Overall, the results based on the parish contexts support the patterns found in the main analyses. Since the parishes are considerably larger than the individualized neighbourhoods, this also suggests that similar patterns of Gx \times E are also operating at a larger scale than the most proximal social contexts.

Conclusion

In the closing remarks of the very first twin study of voting, the authors emphasized that future research should "explore the interaction effects of genes and environment on participation" (Fowler et al. 2008, p. 244). Building on recent discoveries of a causal relationship between individual-level genetic propensities for educational attainment, this study makes a direct and significant contribution to the genetically informed literature on political participation by showing that the effect of education-related genetic resources on participation differ depending on proximal social contexts during the formative years.

In so doing, this study connects back to key works in the political participation literature like that of Huckfeldt (1979), which highlights the importance of studying individual-level resources in conjunction with the social environment that individuals are embedded in. It also connects to previous work on the sorting model of education (Campbell 2009; Persson 2011), which also posits an environmentally conditional effect of individual-level education on participation. In relation to the emerging social science genetics literature, it is one of the first studies to systematically

⁸ Parish identifiers are available in 1960, 1965 and then annually between 1968–2014. To create the equivalent parish measures of political engagement and SES, full-population data was aggregated within existing parishes between 1960 and 2014, following the same approach as before with regards to assigning existing register data, and were then assigned to the twins. The twins born 1940–1944 were assigned their parental parish in 1960, those born in 1945–1949 were assigned their (personal) parish in 1960, and those born in 1950–1952 were assigned their parish in 1965. Twins born 1953 and onward were assigned their parish exactly at age 15. To see how existing register data was used to create the parish contexts, see Table A6.

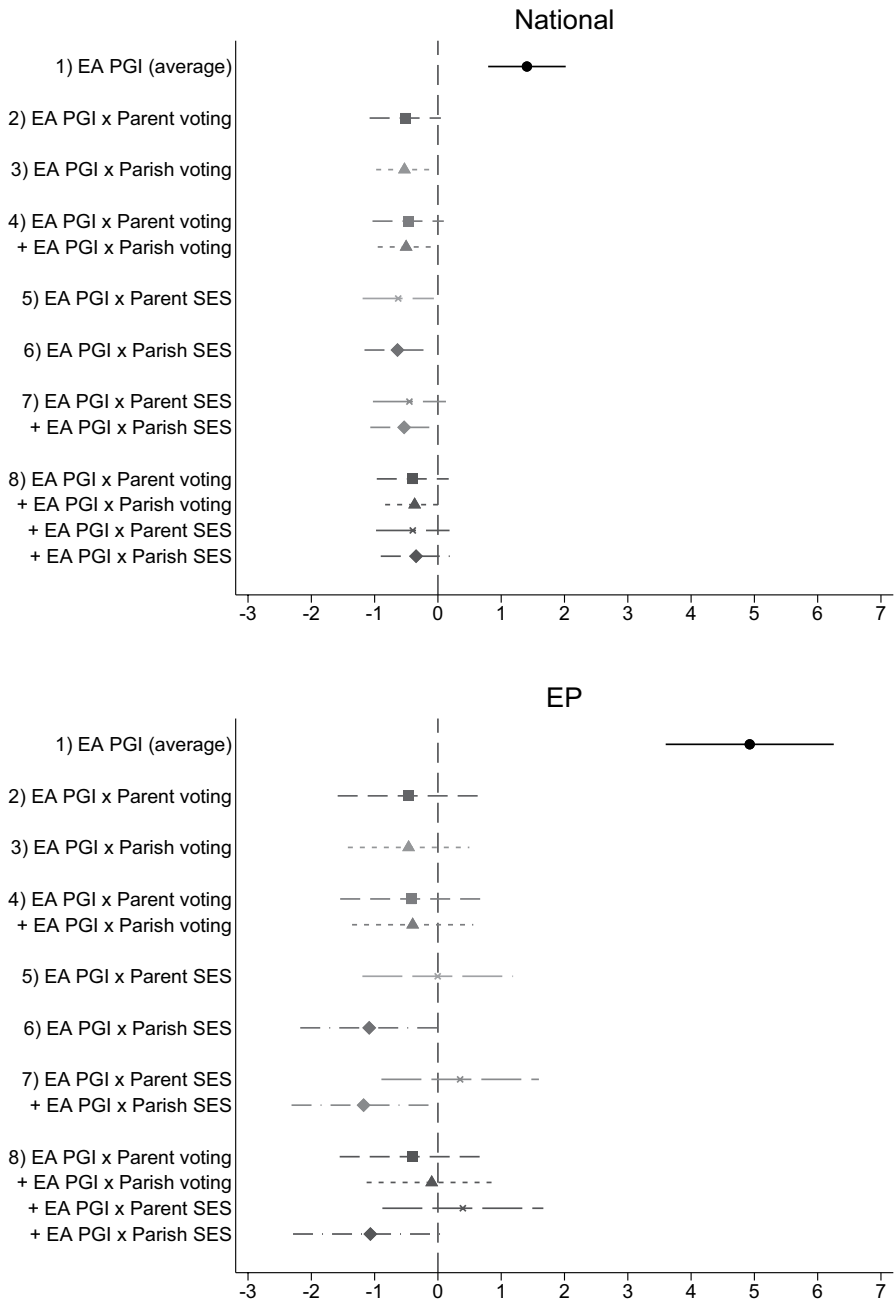


Fig. 4 Results from parish-based gene-environment interaction models. Estimates are shown with 95 percent confidence intervals. Color shades correspond to models. Marker symbols correspond to variables and interaction terms

explore the interaction between individuals' genetic propensities and neighbourhood characteristics with regards to social life outcomes, and definitely the first to do so with regards to the societally valued outcome of political participation. In its application of highly fine-grained individualized neighbourhoods, it also contributes by going beyond pre-defined administrative areas as measurements of neighbourhoods in a study of gene-environment interaction.

In lockstep with e.g. Verba et al. (1995), two key environmental characteristics were assessed: the strength of political engagement, and of SES. While it has been suggested previously that participation-conducive environments ought to trigger genetic influences on participation (Boardman 2011), this study finds evidence to the contrary: both these characteristics seem to reduce the effect of within-family differences in genetic resources on voting, in line with the notion that an advantageous environment can compensate for genetic disadvantages. For voting in first-order, national elections, parental political engagement comes out as the most consistent moderator, although the combined evidence is arguably sufficient to suggest that political engagement on the neighbourhood level, as well as parental and neighbourhood SES, also has a suppressing impact on the genetic effect. With regards to second-order, EP elections, the results are mostly very similar, although neighbourhood-level characteristics may potentially be more important moderators in this case than parental characteristics. Additional analyses suggest that these interactions are approximately linear in nature, are reproducible using variations of the genetic predictor, are unlikely to be merely the result of a methodological artifact, and do not simply capture geographical differences in genetic ancestry. The main results concerning neighbourhood interactions could also be replicated using pre-defined administrative contexts, in the shape of parishes, using a markedly larger sample. A key insight from the supplementary rolling regressions analyses is also that the within-family effect of education-related genetic resources, at least on voting in national elections, cannot clearly be distinguished from zero within the most favourable family and neighbourhood contexts. This could suggest that the effect of genetic resources can, in fact, be mostly or entirely overridden by the environment.

Theoretically, then, the results suggest a mechanism where the participatory importance of genetic resources are reduced by proximal environments that are themselves conducive to participation. Growing up with parents or neighbours that are themselves politically engaged may make it more likely that individuals will be mobilized, and that they will internalize participatory norms, which in turn reduces the voting differential that stems from pre-existing inequalities in genetic resources. Additionally, to grow up with access to an abundance of socioeconomic resources can be instrumental with regards to acquiring the key skills that matter for participation, and that can thereby compensate for differences in 'innate' abilities (such as cognitive skills). In contrast, environments deprived of political activity and of resources may be expected to accentuate genetic differences, leaving individuals to their own genetic devices when it comes to becoming a participating adult. These results align with the findings of a recent gene-environment interaction study showing that contextual SES decreases EA PGI effects on educational performance (Silva et al. 2025).

Despite its strengths and contributions, limitations to the study should be noted. The first concerns the conceptualization of education-related genetics as genetic

resources. While this study has treated such genetics, as measured by the EA PGI, as a fundamental indicator of individuals' genetic resources, and while existing studies point to these genetics as the most important predictor of participation, the EA PGI tends to be a substantial predictor of many other auxiliary outcomes as well (see e.g. Barban et al. 2016; Pasman et al. 2022; Okbay et al. 2022; Ericsson et al. 2024; Kweon et al. 2025). This could be because education-related genetics are important for a wide range of outcomes, but it could also be because the EA PGI is based on the currently largest GWAS samples, and therefore has the largest overall predictive power. In other words, there could also be other genetic resources of importance for participation that are not necessarily related to education, and that will not necessarily interact with the environment in the same way. While on this point, while the EA PGI is the most powerful genetic predictor available, the fact that the SNPs that make up the PGI are estimated in a finite sample introduces measurement error, biasing the PGI estimates downwards. This problem is also compounded further when the PGI is modelled within families. Additionally, the genetic variants included in the PGI are, again, likely to be biased towards *not* varying across environments. It is therefore not unlikely that the discovered interactions are larger in reality.

It is also worth emphasizing again that, while a causal identification of genetics could be achieved, we need to be open about the possibility that the measured environmental characteristics are at least partly capturing something different, and that has gone unmeasured. Robustness tests indicated that they do not appear to reflect mere geography, but the issue remains. This is an issue that researchers in social science genetics often face: having to choose between a stringent identification of the genetic *or* the environmental variable (cf. Ahlskog 2024; Biroli et al. 2025). In this case, it has arguably been more important to have a robust measurement of individuals' genetics, since confounding of the genetic effect complicates interpretations significantly. Nevertheless, this is an important limitation that could potentially be addressed by combining exogenous or quasi-exogenous shocks to SES or political engagement with within-family measurements of genetics, given that a large enough sample could be assembled for such an analysis. Strengthening the causal identification of both genetics and environments remains an important task for future inquiries.

Related to the above, another limitation concerns the operationalization of political engagement. The level of turnout may leave out important aspects of what makes a social context politically vibrant, and one could certainly argue that it is a too coarse measure. Nevertheless, it should be represent a feasible proxy for the overall level of political engagement and activity, and a notable advantage is that, since turnout can be measured for virtually *all* Swedish citizens, political engagement can be measured with high precision all across Sweden. Had one been confined to using survey data, this would unlikely have provided similar geographical coverage, and it would not have been possible to obtain survey data for all parents.

Some limitations related to the country case and the sample also apply. The costs of voting in Sweden are low compared to some other democracies; citizens are automatically registered to vote, elections always take place on a non-work day, and there are extensive opportunities for voting ahead of election day. It would be quite interesting in future research to assess whether the results can be generalized to countries where the costs of voting are higher. Additionally, the STR sample is

not perfectly representative of the Swedish population. STR twins tend to be more highly educated than the average Swedish individual, and the turnout in STR is also higher than in the general population. Studies of more representative samples would be a way to improve on the current study. Another topic that should be of interest to future research is whether the results extend to other forms of participation. Voting, particularly in first-order elections, is a collective and highly institutionalized form of participation. It is possible that different patterns of gene-environment interaction could arise in a study of more individualized, and more costly forms of participation.

It is well-established that for political equality to be fulfilled, differences in participation should only be the result of differences in individuals' motivation to participate, and not underlying differences in resources (cf. Verba et al. 1995; Lindgren and Oskarsson 2023). In other words, citizens should have equal *opportunity* to participate. The fact that genetic propensities for educational attainment has an average effect on voting indicates a genetically based participatory inequality of opportunity. But when taking environmental characteristics into account, this inequality – despite its deep-rooted origins – appears to be environmentally malleable at least to some extent. For those individuals that are able to reap the benefits from growing up in politically as well as socioeconomically strong environments, the genetic basis of participatory inequality appears to be mitigated.

This study thereby highlights the interdependency of genetic and environmental inequalities, and indicates the politically equalizing implications of raising the socioeconomic status of disadvantaged families and neighbourhoods, or at least compensating for these disadvantages through other key institutions, such as the school. Promoting participation and other forms of engagement among less politically active adults, for instance through targeted outreach programs, or by emphasizing the importance of participation in the school environment, could also serve to ensure that younger generations adopt pro-participatory norms that reduce the elbow room for genetics to manifest. Genetic influences on social life outcomes are sometimes interpreted as implying the imperviousness of societal inequalities to political intervention (see e.g. Manski 2011). Regardless of what specific policies are adopted, this study provides evidence to the contrary. Nature could, as it were, be overridden.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11109-025-10096-6>.

Acknowledgements The author is very grateful for input and comments from the three anonymous reviewers, as well as from participants at the UCLS Political Inequality Workshop 2024, the MPSA Annual Meeting 2024, and the APSA Annual Meeting 2024.

Funding Open access funding provided by Uppsala University. This research has been generously supported by the Swedish Research Council (2019-00244) and Riksdagens Jubileumsfond (P18-0782:1).

Data Availability and Ethics Approval Statement This study is based on individual-level register data provided by Statistics Sweden, combined with data from the Swedish Twin Registry (STR), which is administered by the Steering Committee of the Swedish Twin Registry. The research conducted has been approved by the Swedish Ethical Review Authority (Dnr 2017/083), and by the Steering Committee of the Swedish Twin Registry. The used data material is located on an encrypted server onto which one has to log in through a remote desktop application in order to perform all of the data analyses. Due to the high sensitivity of these data, the author is under contractual and ethical obligation not to distribute these data to

others. For those researchers who want to replicate the results, they must obtain approval from the Swedish Ethical Review Authority and from the Steering Committee of the Swedish Twin Registry. Researchers using STR data are also required to follow the terms of a number of clauses designed to ensure protection of privacy and compliance with relevant laws. For further information, visit <https://ki.se/en/research/swedish-twin-registry-for-researchers>. The relevant Stata scripts used to assemble the data and perform the analyses can be found here: https://osf.io/d9z5c/?view_only=468c6d0128764f148c627e02241cce9f.

Declarations

Conflicts of interest The author has no conflicts of interest to disclose.

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