

Economic Theory of Fertility Explains Modern Natural Selection

David Hugh-Jones (D.Hugh-Jones@uea.ac.uk), Abdel Abdellaoui (a.abdellaoui@gmail.com)

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Abstract

Natural selection has been documented in contemporary humans, but little is known about the mechanisms behind it. We test for natural selection on 33 polygenic scores over two generations, using data from UK Biobank. Selection effects appear consistent over time. Polygenic scores which predict lower earnings and education are selected for. Effects are concentrated among low-income and less educated people, younger parents, people with more lifetime sexual partners, and people not living with a partner. Overall effect sizes are substantially larger after correcting for ascertainment bias. The direction of natural selection is reversed among older parents, or after controlling for age at first live birth. These patterns can be explained by economic theories of fertility, in which higher earnings may either increase or decrease fertility.

Living organisms evolve through natural selection, in which allele frequencies change in the population through differential reproduction rates. Geneticists have long hypothesized that natural selection is taking place in modern human populations. Recent work confirms this using genome-wide analysis (Barban et al. 2016; Beauchamp 2016; Kong et al. 2017; Sanjak et al. 2018). In particular, genetic variants associated with higher educational attainment are being selected against, although effect sizes appear small.

As yet we know little about the *mechanisms* behind natural selection in contemporary human populations. This study uses data from UK Biobank to learn more. We test for natural selection on 33 different polygenic scores. We extend the analysis over two generations, using data on respondents' number of siblings as well as their number of children. This is interesting because consistent natural selection over multiple generations could lead to substantive effects in the long run.

Most importantly, we examine reproductive rates in different subgroups of the population, in order to uncover patterns that can help illuminate the mechanisms behind modern natural selection. We find that across the board, polygenic scores have stronger relationships with fertility in specific subgroups of the population. Furthermore, in some subgroups, the direction of relationships is actually reversed.

These patterns can be explained by economic theories of fertility (Becker 1960). In these, higher potential earnings have two opposite effects on fertility: a fertility-increasing *income effect* (higher income makes children more affordable), and a fertility-lowering *substitution effect* (time spent on childrearing has a higher cost in foregone earnings). Our results suggest that the substitution effect dominates for single parents, while the income effect is stronger for couples.

Data and methods

We use data from UK Biobank. Our sample consists of white British (as defined by genetic estimated ancestry). For regressions on number of children we limit the sample to people over 45, since most fertility is completed by this age.

We compute 33 polygenic scores, normalized to mean 0, variance 1. Figure 1 plots mean polygenic scores by 5-year birth intervals. Several scores show consistent increases or declines over this 30-year period, of the order of 5% of a standard deviation.

These changes could reflect either natural selection within the UK population, or ascertainment bias within the sample. Respondents are higher income and better educated than the UK population, and they may also differ on other unobserved characteristics (Fry et al. 2017). Since richer and educated people also live longer, this bias might also increase with age.

We next regress respondents’ polygenic scores on their number of children (y_i):

$$y_i = \alpha + \beta \text{PGS}_i + \varepsilon_i \tag{1}$$

The “selection effect”, β , measures the strength of natural selection within the sample. In fact, since polygenic scores are normalized to mean 0, β is the expected polygenic score among children of the sample (Beauchamp 2016). To learn more about the underlying mechanisms, we split the sample, starting with basic demographic variables including education, income and sex. These are all potential sources of ascertainment bias: as well as the ascertainment for income and education, mentioned above, the sample sex ratio skews 54.05% female.

Figure 2 plots selection effects for each polygenic score, grouping respondents by age of completing full-time education, and by household income. Effects are larger and more significant for the lowest income category, and for the lowest education category. Note that the overall effect is not a simple average of the effect among the different subgroups, because polygenic scores may also shift respondents between the subgroups. For example, a high PGS for educational attainment may correlate with fewer children among early school leavers, but may also increase the age at which a respondent leaves school.

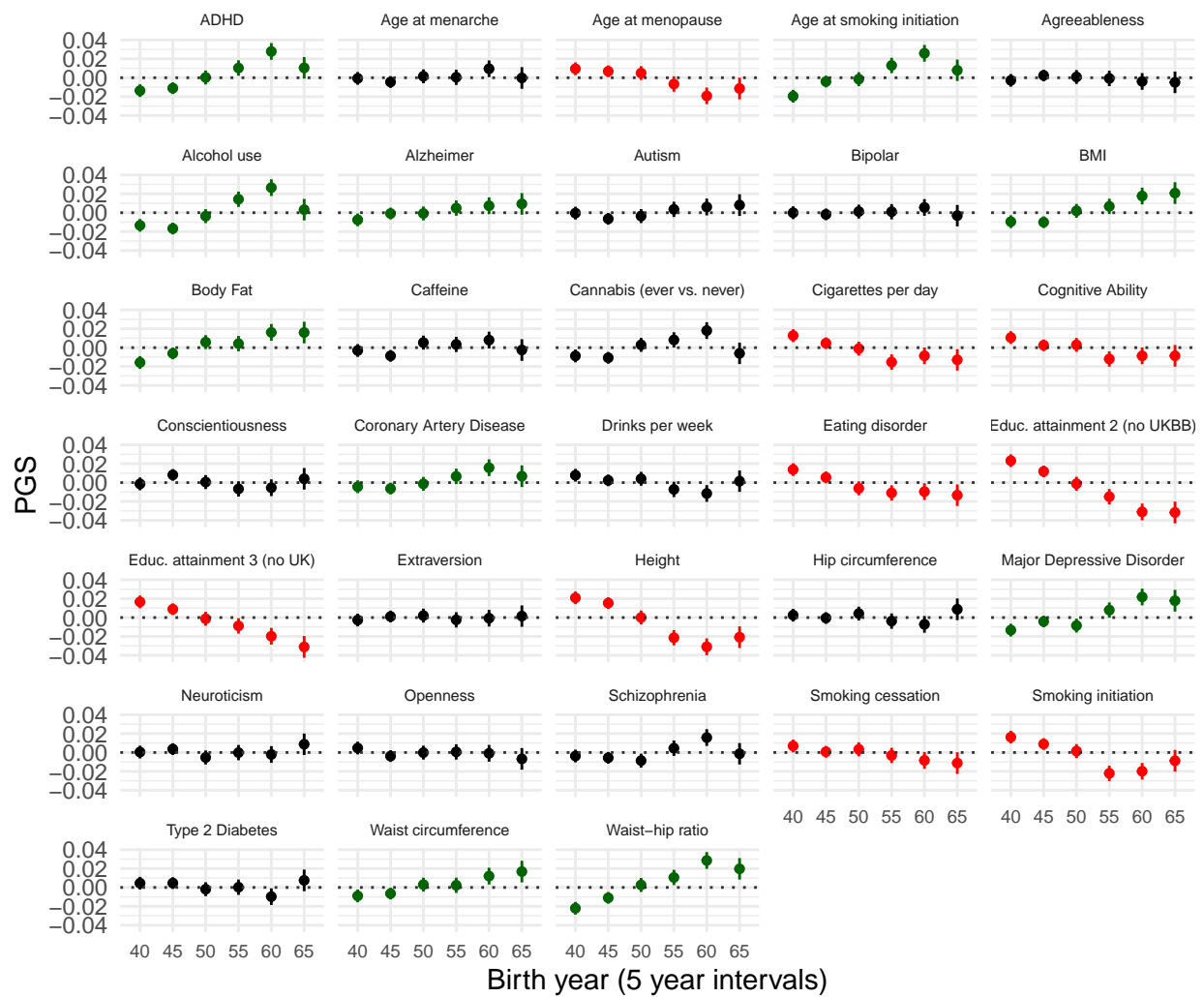
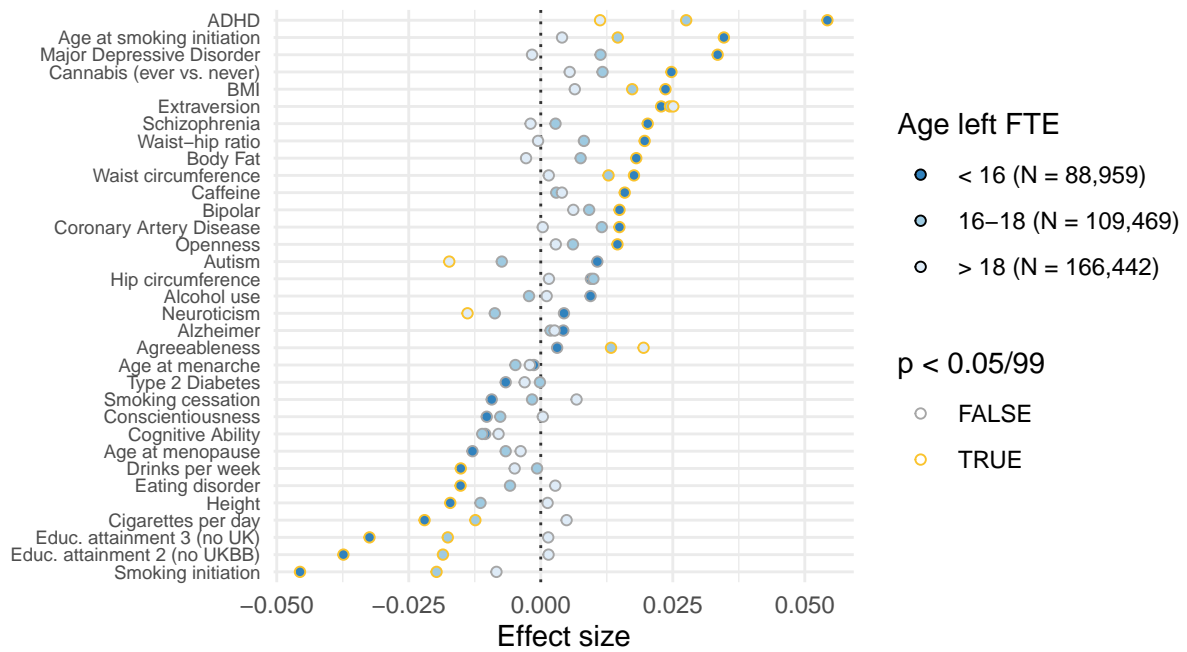
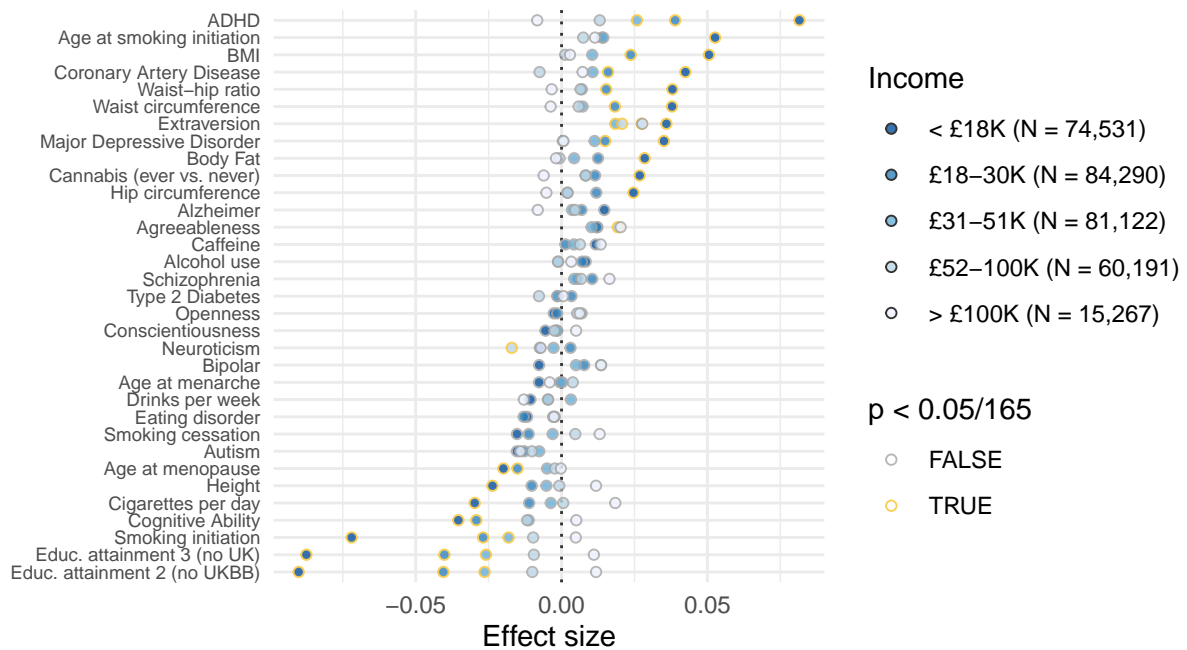


Figure 1: Mean polygenic scores by birth year in UK Biobank. Points are means for 5-year intervals. Lines are 95% confidence intervals. Green lines show a significant linear increase over time ($p < 0.05/33$). Red lines show a significant decrease.



(a) Age left full-time education



(b) Household income

Figure 2: Selection effects by education and income

These results could be driven by age, if older respondents are poorer and less educated, and also more subject to selection on polygenic scores. However, if we rerun the regressions, interacting the polygenic score with income category and also with a quadratic in age, the interaction with income remains significant at 0.05/33 for 16 out of 33 regressions. Similarly if we interact the PGS with age of leaving full time education and a quadratic in age, the interaction with age leaving FTE remains significant at 0.05/33 for 17 out of 33 regressions.

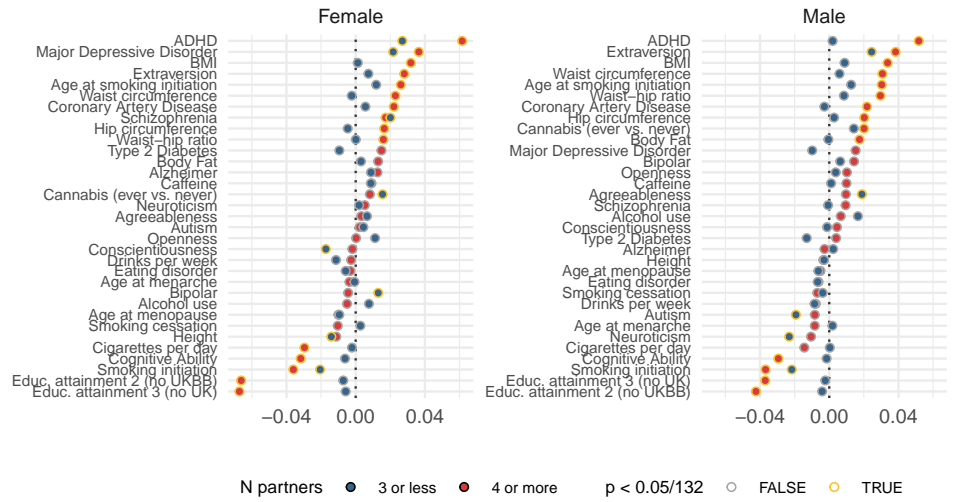
Selection effects are also different between men and women (Appendix Figure 7). Differences are particularly large for educational attainment, height and MDD. Several PGS for mental illness and personality traits are more selected for (or less against) among women, including major depressive disorder (MDD), schizophrenia and neuroticism, while extraversion is more selected for among men. Waist circumference and waist-hip ratio are less selected for among women, and educational attainment is more selected against, though the difference is only significant for EA3. One possible reason for these sex differences is that polygenic scores may affect fertility via mate search.

We next focus on variables related to mate search and household formation. We split males and females by lifetime number of sexual partners, at the median value of 3 (Figure 3a). For both sexes, selection effects are larger and more significant among those with more than 3 partners. Splitting respondents by whether they were living with a spouse or partner at the time of interview, effects are larger among those not living with a spouse or partner (Figure 3b). Lastly, we split female respondents by age at first live birth (AFLB).¹ There is evidence for genetic effects on AFLB (Barban et al. 2016), and there is a close link between this variable and number of children born. Figure 3c shows effect sizes estimated separately for each tercile of AFLB. Several effects are strikingly different across terciles. ADHD and MDD are selected for amongst the youngest third of mothers, but selected against among the oldest two-thirds. Educational attainment is selected for among the oldest two-thirds of mothers, but is not significantly selected among the youngest third. Similarly, several PGS of body measurements are selected against only among older mothers. The correlation between effect sizes for the youngest and oldest terciles is -0.51. As before, recall that PGS may have two effects: changing the number of children within each category, and changing the number of children by shifting respondents between categories.

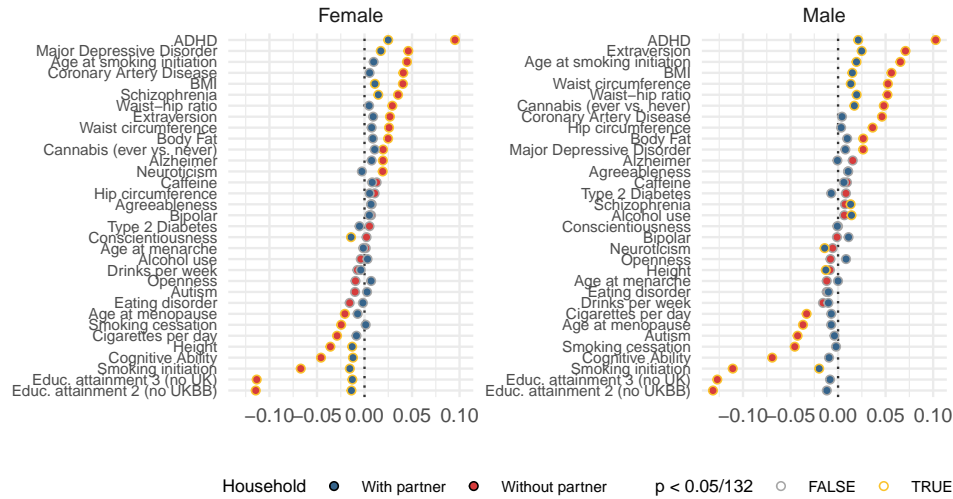
To investigate this further, we regress number of children on PGS *controlling* for AFLB (appendix Figure 8). In 24 out of 33 cases, effects change sign when controls are added. The correlation between effect sizes controlling for AFLB, and raw effect sizes, is -0.72. Selection effects appear to come through two opposing channels: an effect on AFLB, and an opposite-signed effect on number of children controlling for AFLB.

Since UK Biobank subjects are not representative of the wider population, our results suggest that naïve estimates of natural selection are at risk of ascertainment bias. To correct for this, we weight participants using data from the 2011 Census and from the 2006 General Household Survey (GHS). We try three alternative weighting schemes: ge-

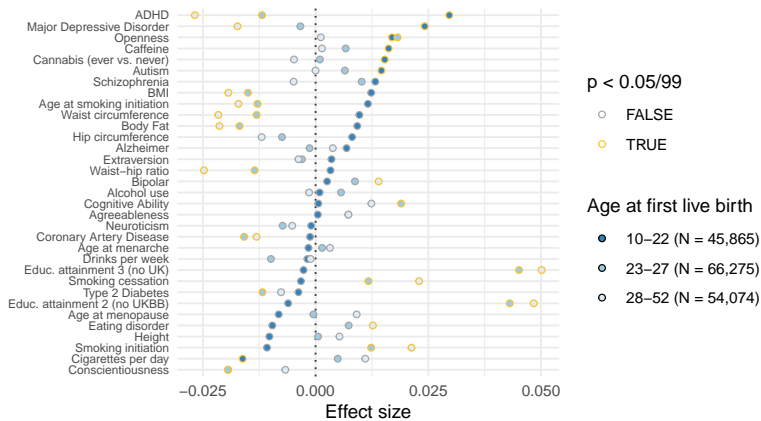
¹This information is unavailable for men.



(a) Lifetime number of sexual partners



(b) Household type



(c) Age at first live birth, females

Figure 3: Selection effects by number of sexual partners, household type, and age at first live birth

ographical weighting by census MSOA, age and presence/absence of a partner; weighting by age and highest educational qualification; and age, highest qualification, and age at first live birth, for women only. Mean effect sizes across all polygenic scores are increased by a factor of 1.33 (geographical weighting), 1.21 (age/qualification) or 1.76 (age/qualification/AFLB). Estimates might be further affected by weighting on other demographic variables. Since the Biobank sample seems to be ascertained in ways that shrink estimates of selection effects, we suspect that our weighted estimates are still conservative.

The UK Biobank data contains information on respondents' number of siblings. Since respondents' polygenic scores are equal in expectation to the mean scores of their parents, we can use this to look at selection effects in the parents' generation. We estimate equation (1) using *number of siblings* (including the respondent) as the dependent variable. The parents' generation has a further source of ascertainment bias: sampling parents of respondents overweights parents who have many children. For instance, parents of three children will have, on average, three times more children represented in UK Biobank than parents of one child. Parents of no children will by definition not be represented. To compensate, we reweight our preferred weightings (Age/Qualification) by the inverse of *number of siblings*.

Selection effects are highly correlated across the two generations, and most share the same sign (appendix Figure 10). Effect size estimates are larger for the parents' generation. We treat this result cautiously, because when we split respondents up by year of birth, we find few differences in effect sizes between early- and late-born respondents, for either generation. In other words, since estimated effect sizes change when we change the dependent variable, but do not change over time within either dependent variable, this may be due to remaining ascertainment bias within the sample.

Although the direction of selection effects does not change between the generations, there are other differences. After we residualize polygenic scores on the first 100 principal components of the array data, selection effects on *number of siblings* are reduced by about ten percent on average, whereas effects on *number of children* barely change (appendix Figure 11). This could be because earlier fertility is driven more by geographically clustered deprivation (e.g. via an insurance motive, Rendall and Bahchieva 1998), which may correlate with the broad-scale genetic variation captured by principal components. Another difference is that in the parents' generation, raw selection effects and effects controlling for AFLB are positively correlated, whereas they are negatively correlated in the respondents' generation.² These differences suggest that the mechanisms of natural selection may have changed over time, even though the outcomes are broadly the same.

We also check whether selection effects differ by socio-economic status in the parents' generation. We have no information about parents' income, so we use the 1971 Townsend deprivation score of respondents' birthplace as a

²Educational attainment is an exception. It is selected against in the parents' generation, but selected for if we control for AFLB, which is the same pattern we observe among the respondents' generation.

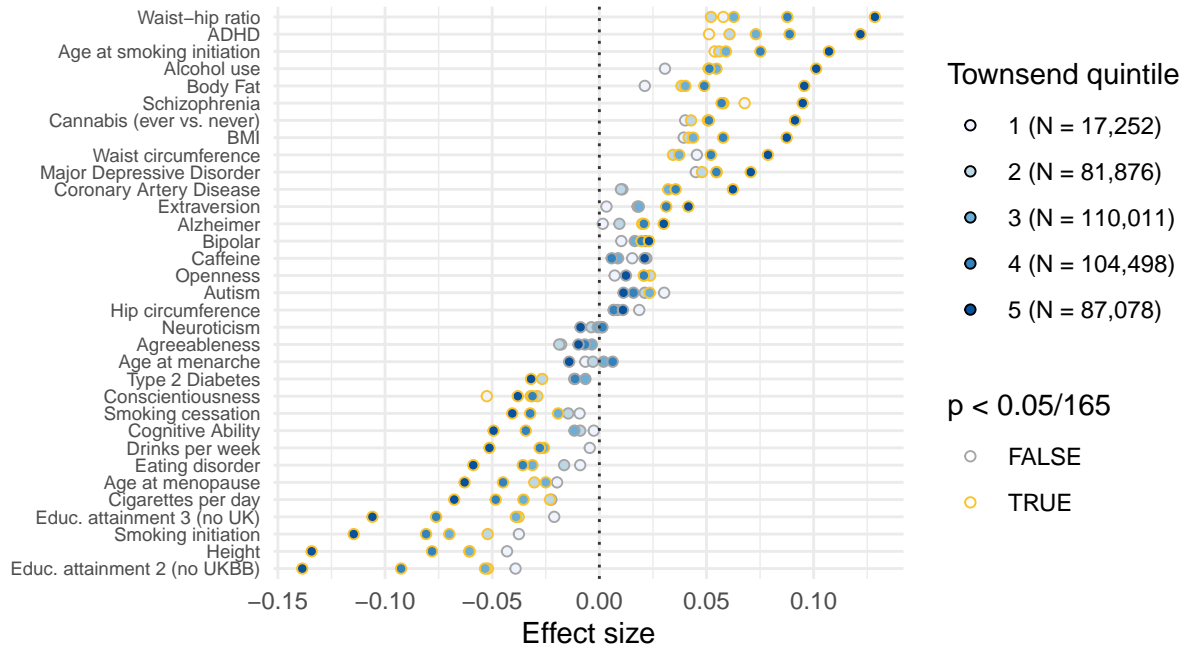


Figure 4: Selection effects in the parents' generation by area Townsend deprivation quintile

proxy (Townsend 1987). Results (Figure 4) show the same pattern as for respondents: effect sizes are larger and more significant in the most deprived areas.

Lastly, the siblings data lets us check for a “quantity-quality tradeoff” between number of children and number of grandchildren (for the parents' generation). We do not find any: in fact, the correlation between *number of siblings* and *number of children* is 0.1.

Our empirical results can be explained by the economic theory of fertility (Becker 1960; Willis 1973; Becker and Tomes 1976). According to this, increases in a person's wage affect their fertility via two opposing channels. There is an *income effect* by which children become more affordable, like any other good. There is also a *substitution effect*: since childrearing has a cost in time, the opportunity cost of childrearing increases if one's market wage is higher. The income effect would lead higher earners to have more children. The substitution effect would lead higher earners to have fewer children. If so, then genetic variants which affect earnings potential in the labour market may cause opposing effects on fertility. The income effect will cause natural selection in favour of earnings-increasing variants. The substitution effect will do the reverse.

This theory predicts that genetic variants will be selected for (or against) in proportion to their effect on earnings. Figure 5 plots selection effects on each PGS against that PGS's correlation with earnings in a respondent's first job³, and against its correlation with educational attainment, a predictor of lifetime earnings. The raw relationships (left

³Earnings are estimated from the 2007 Annual Survey of Hours and Earnings, using the SOC 2000 job code.

column) are strongly negative. If we plot selection effects controlling for age at first live birth (right column), the effect reverses and becomes positive. Thus, the labour market appears to play an important role in natural selection. Substitution effects dominate income effects overall, which fits the empirical association between income and lower fertility (Becker 1960; Jones and Tertilt 2006).

We also re-estimate equation (1) for each PGS, controlling for earnings in first job and education levels. Effect sizes are generally reduced (appendix Figure 16), and only 4 out of 33 PGS are significant at $p = 0.05/33$. This suggests that earnings and education indeed mediate the effect of PGS on fertility.

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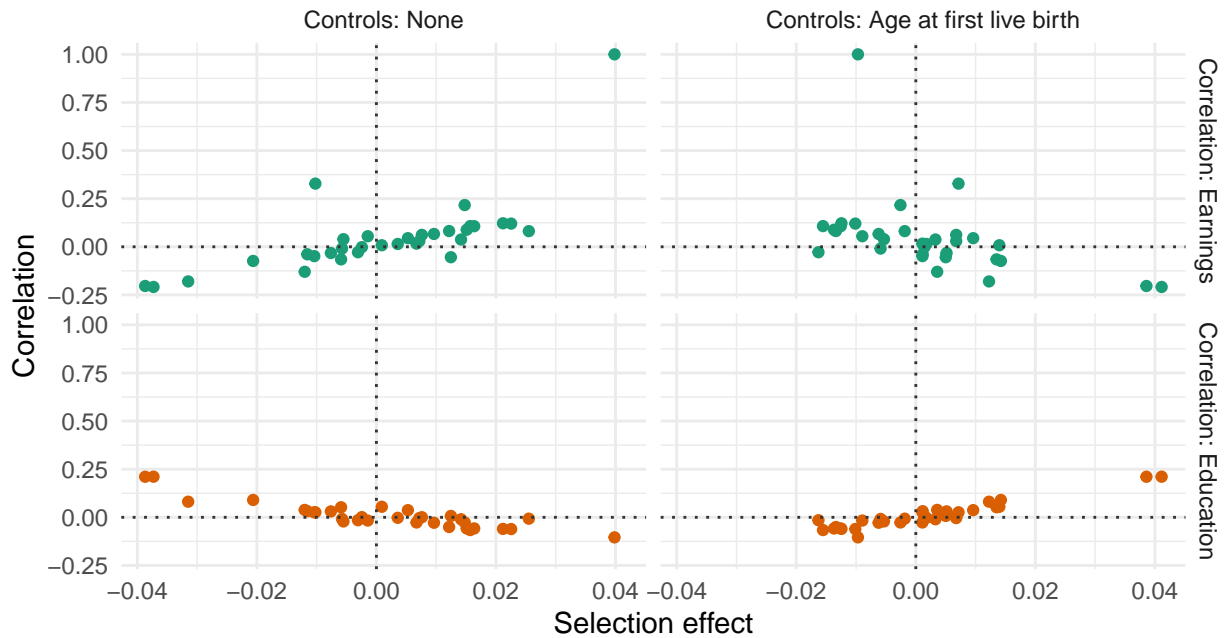


Figure 5: Selection effects, with and without controls for age at first live birth, by correlations with earnings and educational attainment. Each point represents one PGS.

This theory can explain why selection effects have opposite signs when AFLB is controlled for. Suppose that people are aware of their endowments of human capital, i.e. skills and characteristics that are valuable in the labour market. Suppose also that education and innate human capital are complements. Individuals choose how long to stay in education; after leaving education they enter the labour market and form families. If so, then people with less human capital will leave education earlier and have their first child earlier (cf. Caucutt, Guner, and Knowles 2002; Monstad, Proper, and Salvanes 2008). This is a pure substitution effect: the income effect plays no role in the decision to leave education, since people are not yet earning wages.⁴ Whilst in the labour market, higher earners will have more children

⁴This argument assumes that capital market imperfections hinder people from borrowing against future income.

(i.e. income effects dominate). These assumptions will lead to the pattern we observe: earnings-increasing variants will predict later first births (and fewer children overall), but they will also predict more children within any given age at first live birth.

The theory can also explain why natural selection is weaker among higher-income parents. Becker and Tomes (1976) show that if parents care about child quality as well as quantity, under certain assumptions the income effect will be stronger at higher income levels; this can lead to a U-shaped relationship between income and fertility. Empirically, Cohen, Dehejia, and Romanov (2013) find that income decreases fertility at low income levels but increases it at higher income levels.

Lastly, it is often assumed that the substitution effect will dominate for lone parents, or those in unstable relationships, since they have less opportunity to share childcare responsibilities, while the income effect will dominate for couples who are able to reap the gains from specialization. Indeed, US fertility decreases faster with education among single mothers than married mothers (Baudin, De La Croix, and Gobbi 2015). This can explain why earnings-increasing genetic variants decrease fertility more among single parents than among couples. The same logic could explain our results for lifetime number of sexual partners, if this is associated with relationship stability.

An alternative theory is that traits selected for are linked to externalizing behaviour, risk-seeking and low time discount rates, via the channel of early sexual behaviour (Mills et al. 2020). The data here provide some support for this: scores which might plausibly be linked to externalizing behaviour, like ADHD and age at smoking initiation, are selected for. However, this theory is less good at explaining variation in selection across the full range of scores, including physical measures, e.g. waist-hip ratio and BMI (see also appendix Figure 18). Externalizing behaviour also does not explain why selection effects change sign among older parents.

We test the alternative theory directly by re-estimating equation (1) controlling for a measure of risk attitude (Biobank field 2040). While risk attitude is always a highly significant predictor of number of children, it has little impact on the effect size or significance of the PGS. The median ratio of PGS effect sizes between regressions with and without controls is 0.97; all PGS which are significant at $p \leq 0.05/33$ in uncontrolled regressions remain so when controlling for risk attitude. Thus, although risk attitude does predict number of children, it appears not to mediate selection effects. Overall, we believe that the economic theory is the leading explanation.

Discussion

Previous work has documented natural selection in modern populations on variants underlying many polygenic scores (Beauchamp 2016; Kong et al. 2017; Sanjak et al. 2018). We show that natural selection effects are highly concentrated

among specific subgroups of the population, including poorer people, less educated people, younger parents and those with more lifetime sexual partners. Indeed, among older parents selection effects are actually reversed. Furthermore, the size of selection effects on a polygenic score correlates with that score's association with labour market earnings. The economic theory of fertility provides a parsimonious explanation for this.

PGS which correlate with high (low) earnings and more (less) education are being selected against (selected for). In addition, many of the phenotypes under positive selection are linked to poor health, or are what many people would see as undesirable to have. For example, most people would probably prefer to have high educational attainment, a low risk of major depressive disorder, and a low risk of coronary artery disease, but natural selection is pushing against genetics linked to these traits. Potentially, this could increase the health burden on modern populations, but that depends on effect sizes. Our results suggest that naïve estimates can be affected by sample ascertainment bias. This problem may be less serious in surveys which aim to be representative (as the UK Biobank does not). Nevertheless, not all respondents consent to the collection of genetic data: for instance, completion rates for genotype data in the US Health and Retirement Study were around 80-85% (HRS 2020). Researchers should be aware of the risks of ascertainment when studying modern natural selection.

In addition, we do not know whether estimated effect sizes of natural selection will increase or decrease as more accurate polygenic scores are produced. We are also unsure whether genetic variants underlying other phenotypes will show a similar pattern of natural selection as these ones. In short, it is probably too early to tell whether modern natural selection has a substantively important effect on populations' mean polygenic scores.

Because selection effects are concentrated in poorer populations, they also increase inequality with respect to polygenic scores. For example, Figure 6 graphs children's mean polygenic scores for educational attainment (EA3), in households of different income groups. The blue bars show the actual means. The grey bars show the hypothetical means if all households had equal numbers of children. Natural selection against EA3, which lowers the mean, is stronger at the bottom of the income distribution, and this increases the differences between groups.

Any model of fertility is implicitly a model of natural selection. But so far, the economic and human genetics literatures have developed in parallel. Integrating the two could deepen our understanding of modern natural selection. Economics possesses a range of theoretical models on the effects of skills, education and income (see Hotz, Klerman, and Willis 1997, @lundberg2007american). One perennial problem is how to test these theories in a world where education, labour and marriage markets all interact. Genetic data, such as polygenic scores, could help to pin down causality. Conversely, theory and empirical results from economics can shine a light on the mechanisms behind natural selection.

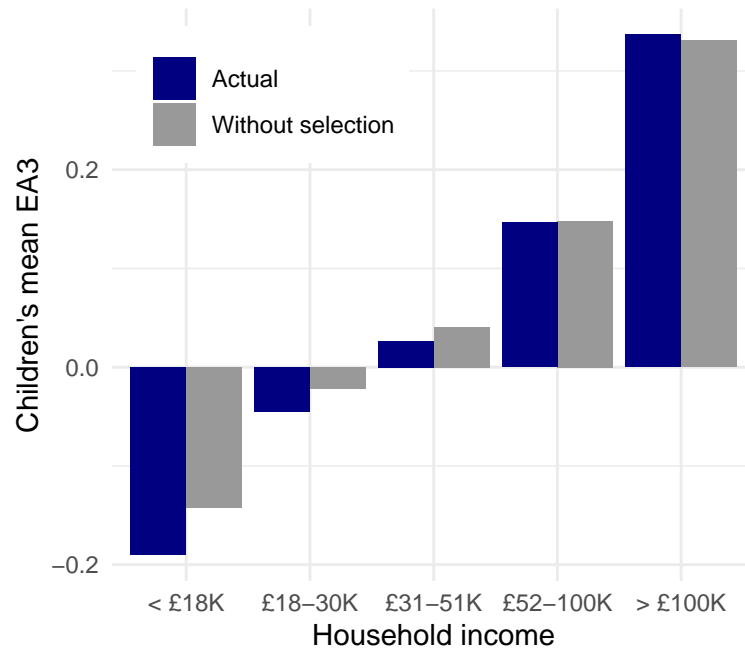


Figure 6: Mean PGS for educational attainment (EA3) of children by household income group. Blue is actual. Grey is hypothetical in the absence of selection effects.

Appendix

Natural selection by sex

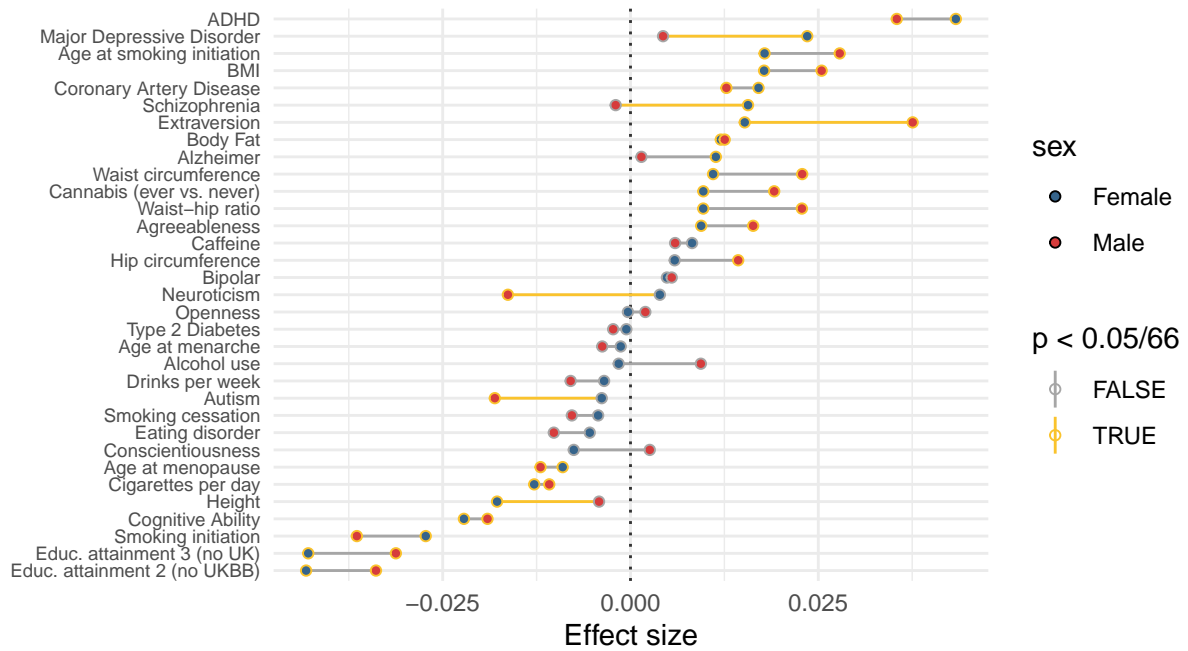


Figure 7: Selection effects by sex. Lines show significant differences.

Controlling for AFLB

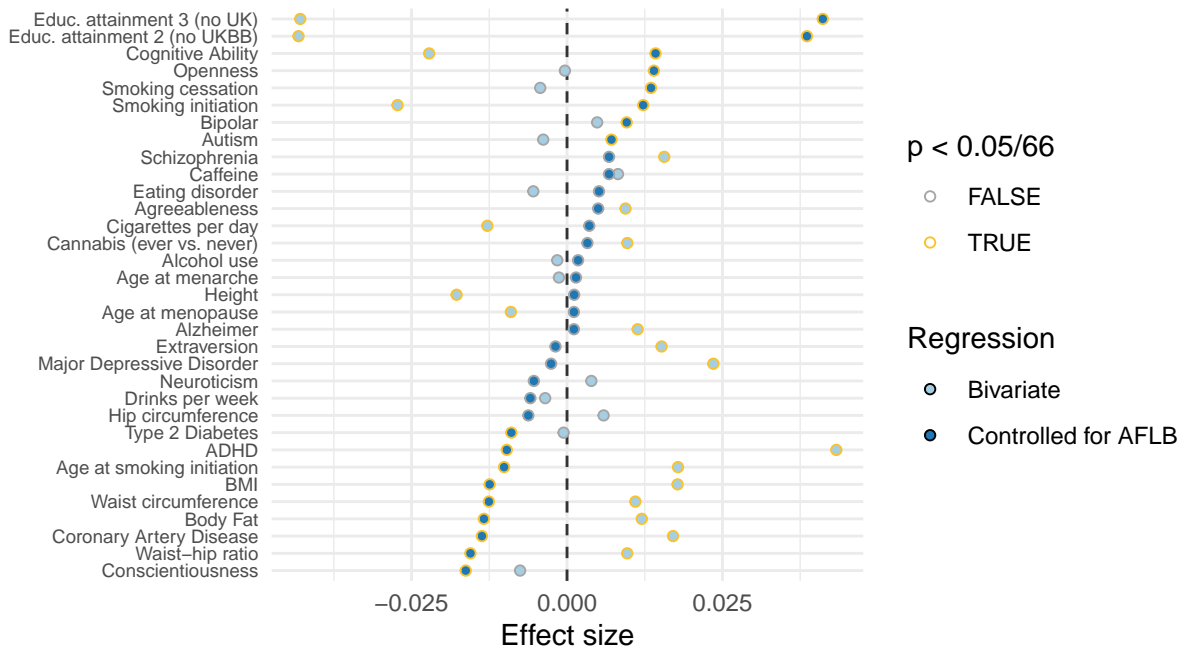


Figure 8: Selection effects controlling for age at first live birth (women only). Effect sizes for women only without controls are shown for comparison.

Weighted regressions

Figure 9 plots effect sizes among the entire sample, using our three weighting schemes. We include unweighted regressions for comparison. Table 1 gives effect sizes as a proportion of the unweighted effect size.

Table 1: Weighted effect sizes as a proportion of unweighted

PGS	Weighting		
	Geographical	Age/Qualification	Age/Qual/AFLB
Cigarettes per day	1.79	1.25	1.97
BMI	1.69	1.21	2.2
Hip circumference	1.67	1.21	3.71
Height	1.6	1.32	1.24
Autism	1.57	0.881	0.75
Educ. attainment 3 (no UK)	1.51	1.46	1.98
Waist circumference	1.51	1.3	2.65
Age at menopause	1.49	1.1	1.18
Major Depressive Disorder	1.49	1.15	1.54
Waist-hip ratio	1.43	1.43	2.14
Educ. attainment 2 (no UKBB)	1.42	1.46	1.93
Alzheimer	1.31	0.623	1.59
Body Fat	1.31	1.39	1.91
Cannabis (ever vs. never)	1.27	1.15	0.859
Smoking initiation	1.22	1.21	1.5
Cognitive Ability	1.2	1.31	2.09
Eating disorder	1.19	1.66	2.05
ADHD	1.15	1.28	1.6
Age at smoking initiation	1.15	1.24	1.63
Coronary Artery Disease	1.11	1.17	1.86
Schizophrenia	1.08	1.3	0.743
Extraversion	1.07	1.15	2.13
Agreeableness	0.959	0.676	0.627
Caffeine	0.808	1.01	2.36
<i>Mean</i>	1.33	1.21	1.76
<i>Median</i>	1.31	1.22	1.89

Only consistent and significant (when unweighted) estimates are shown.

Age/Qual/AFLB as a proportion of unweighted regressions for females only.

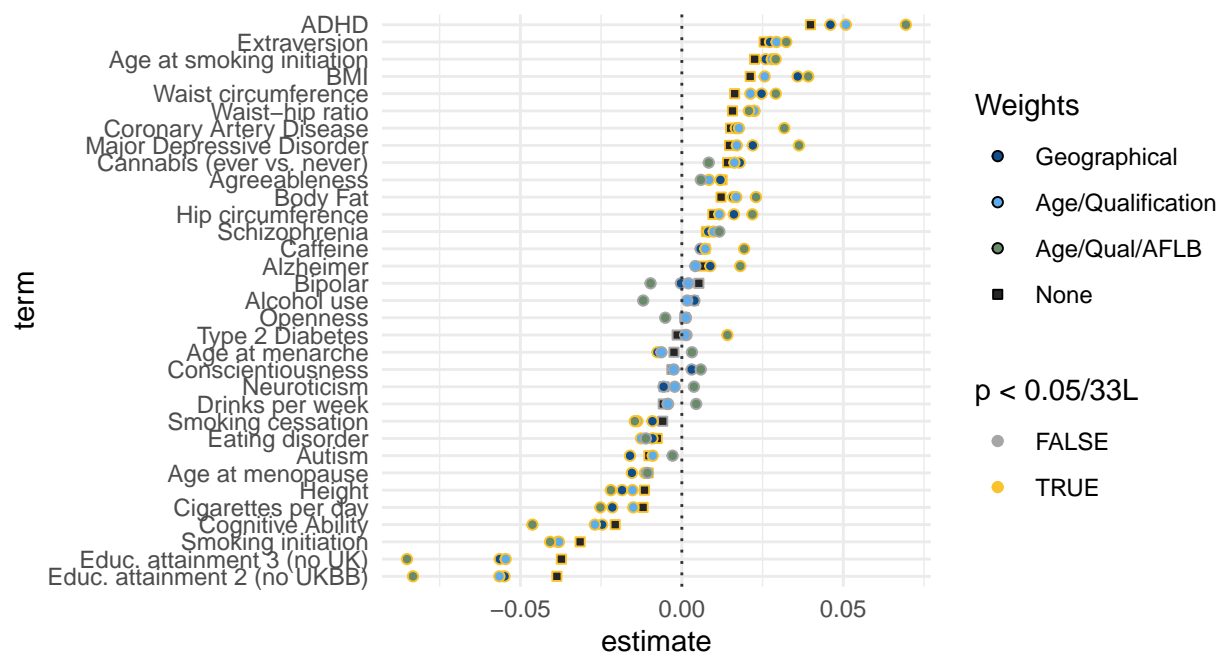


Figure 9: Selection effects: weighted regressions.

Parents' generation

Figure 10 shows regressions of *number of siblings* on polygenic scores. For comparison, we show regressions on the respondents' generation (*number of children*), excluding respondents with no children.

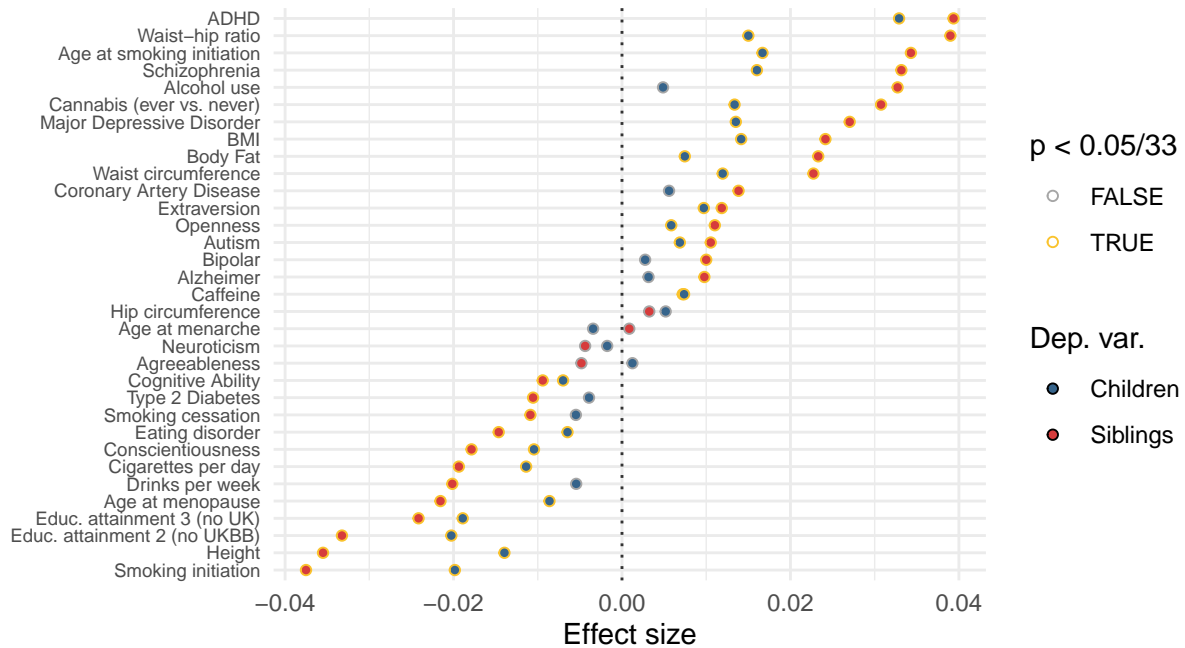


Figure 10: Selection effects, respondents' parents vs. respondents.

To check whether effect sizes were changing over time, we ran regressions interacting PGS with birth year, median split at 1950 ("early born" versus "late born"). We use both *number of children* and *number of siblings* as a dependent variable. We weight using age/qualification cells, and further adjust for selection in the parents' generation (see above).

Tables 2 and 3 summarize the results. There is no change in natural selection within the parents' generation. In the respondents' generation, effect sizes were significantly larger in absolute size among the late-born for four PGS: cognitive ability, EA2, EA3 and extraversion. These changes are inconsistent with the intergenerational change, where effect sizes were if anything larger among the earlier, parents' generation. Three PGS showed significant changes in sign: alcohol use (positive to negative); conscientiousness (negative to positive); and type II diabetes (negative to positive). Overall, there is weak evidence for change over time, and the clearest result is that the direction of selection is broadly consistent.

Table 2: Change in selection effects between parents of early and late born respondents (regressions on number of siblings)

Change	Number of scores
Insignificant	33

Significance is measured at $p < 0.05/66$

Table 3: Change in selection effects between early and late born respondents (regressions on number of children)

Change	Number of scores
Change sign	3
Insignificant	26
Size increasing	4

Significance is measured at $p < 0.05/66$

Controlling for principal components

Polygenic scores could capture effects that are really due to population stratification, although would not change our results for natural selection of the scores. Figure 11 shows selection effects on polygenic scores residualized for the top 100 principal components of the genetic data, calculated within the UK Biobank population.

In siblings regressions, effect sizes are smaller when residualizing for principal components – sometimes much smaller, as in the case of height. 28 out of 33 “controlled” effect sizes have a smaller absolute value than the corresponding “raw” effect size. The median proportion between raw and controlled effect sizes is 0.87. Among the children regressions, this no longer holds. Effect sizes are barely affected by controlling for principal components.

Overall, 81.82 per cent of effect sizes are consistently signed across all four regressions (on children and siblings, and with and without residualization).

To get a further insight into this we regress *siblings* and *children* on individual principal components. As Figure 12 shows, effects are larger and more significant in siblings regressions. 29 principal components significantly predicted number of siblings, while only 10 significantly predicted number of children.

Selection controlling for age at first live birth: respondents’ parents

Among the parents’ generation, we can control for age at first live birth using the subsets of respondents who reported their mother’s or father’s age, and who had no elder siblings. We run regressions on *number of siblings* on these subsets, controlling for either parent’s age at their birth. Figure 13 shows the results. Effect sizes are very similar, whether controlling for father’s or mother’s age. As in the respondents’ generation, effect sizes are negatively correlated with the effect sizes from bivariate regressions without the age at birth control, though the correlation is smaller (father’s

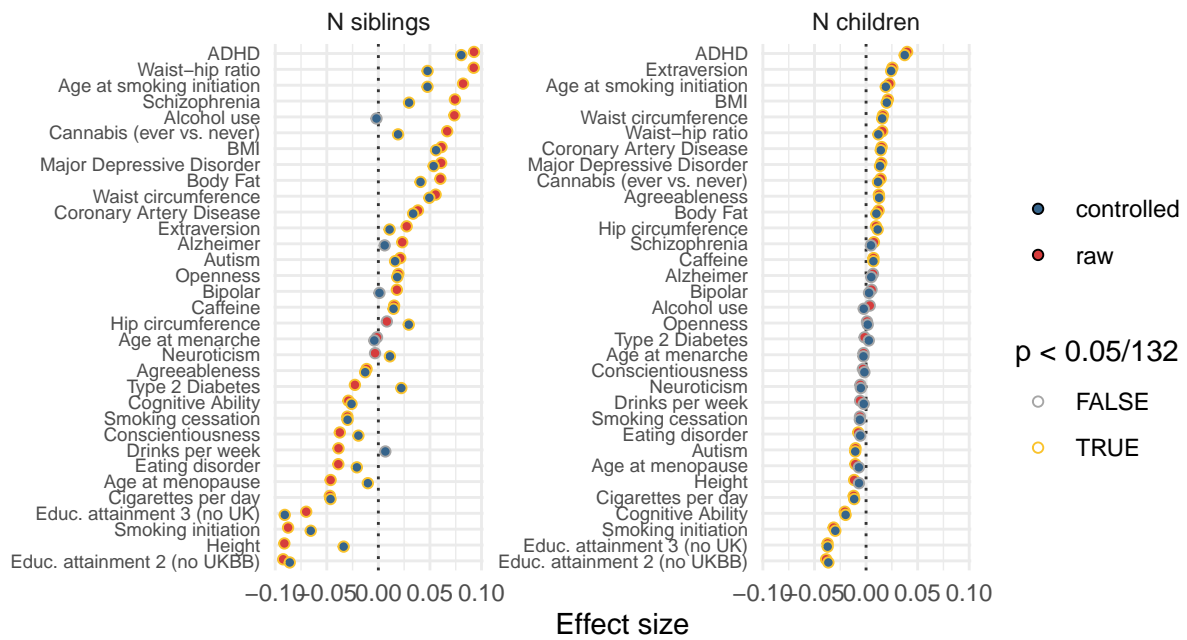


Figure 11: Selection effects using residualized polygenic scores on number of siblings/children.

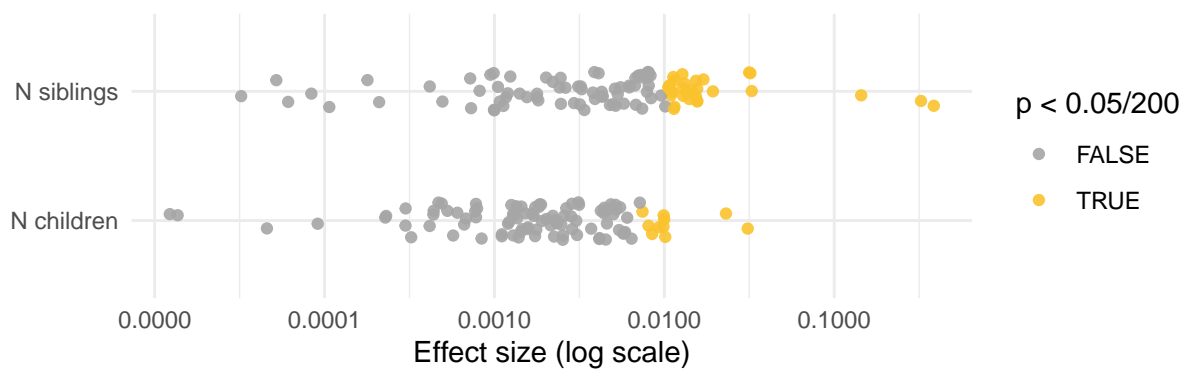


Figure 12: Selection effects of principal components of genetic data. Absolute effect sizes are plotted. Each dot represents one bivariate regression. Points are jittered on the Y axis.

age at birth: ρ -0.08; mother's age at birth: ρ -0.16).

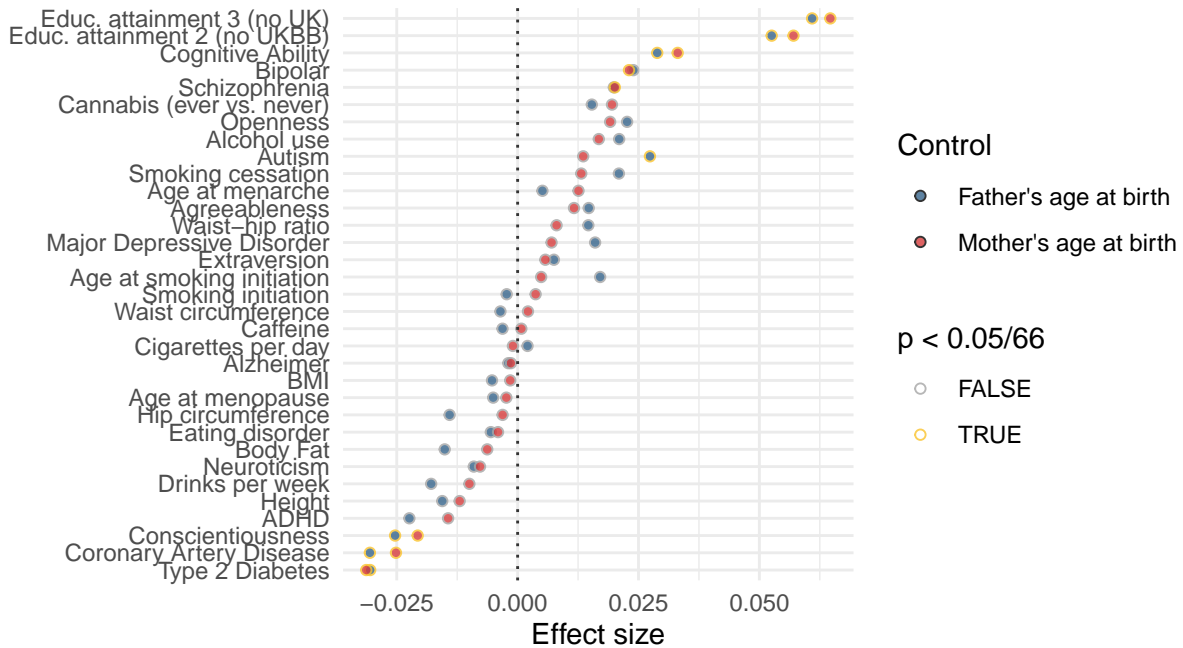


Figure 13: Selection effects (parents' generation) among eldest siblings, controlling for parents' age at birth.

Effects of PGS on age at first live birth

Our results suggest that polygenic scores may directly correlate with age at first live birth. Figure 14 plots estimated effect sizes from bivariate regressions for respondents, and Figure 15 does the same for their parents. Effect sizes are reasonably large. They are also very highly correlated across generations. Effect sizes of PGS on father's age at own birth, and on own age at first live birth, have a correlation of 0.99; for mother's age and own age it is 0.98

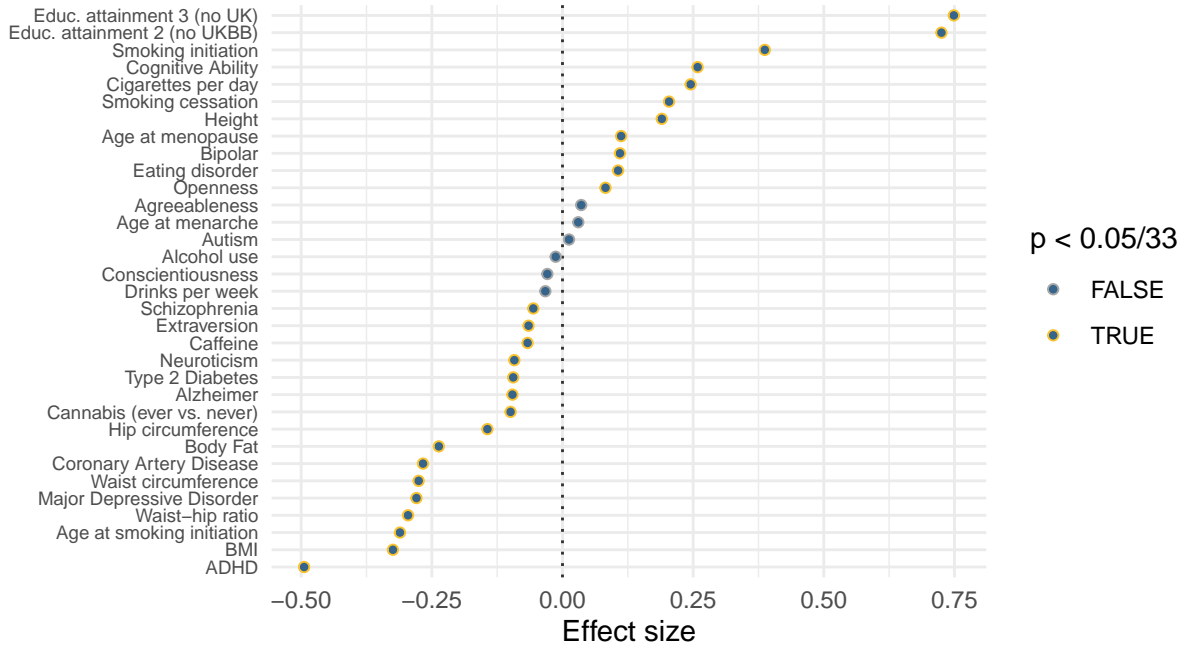


Figure 14: Effects of polygenic scores on age at first live birth.

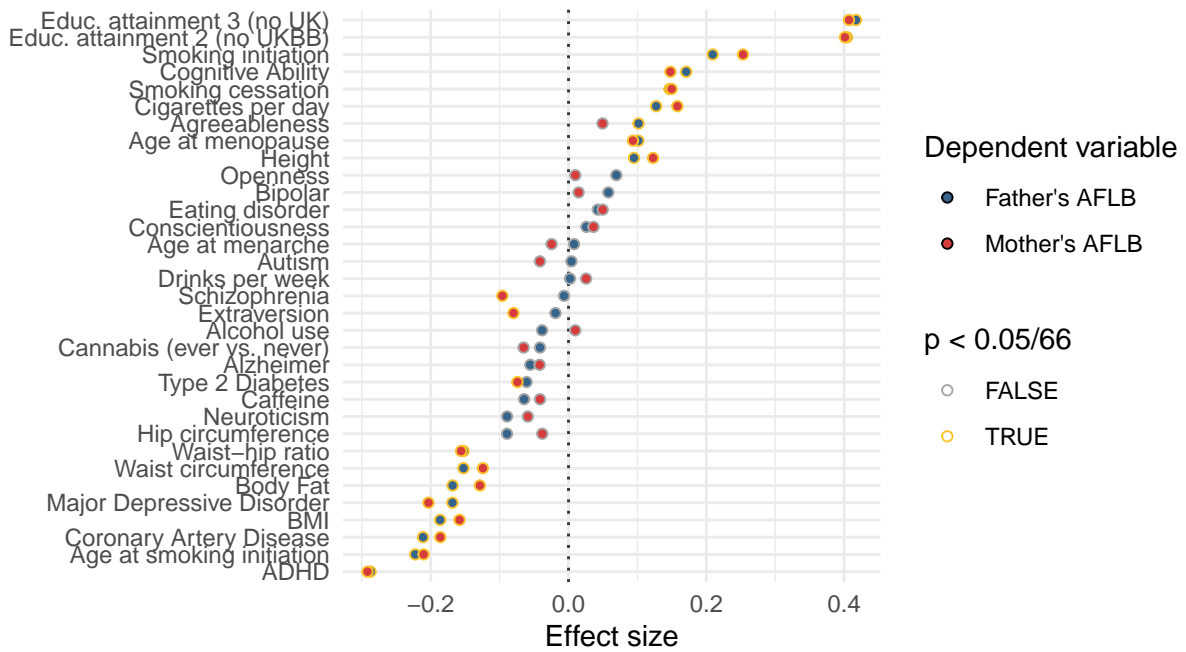


Figure 15: Effects of polygenic scores on parents' age at respondent's birth, eldest siblings.

Controlling for earnings and education

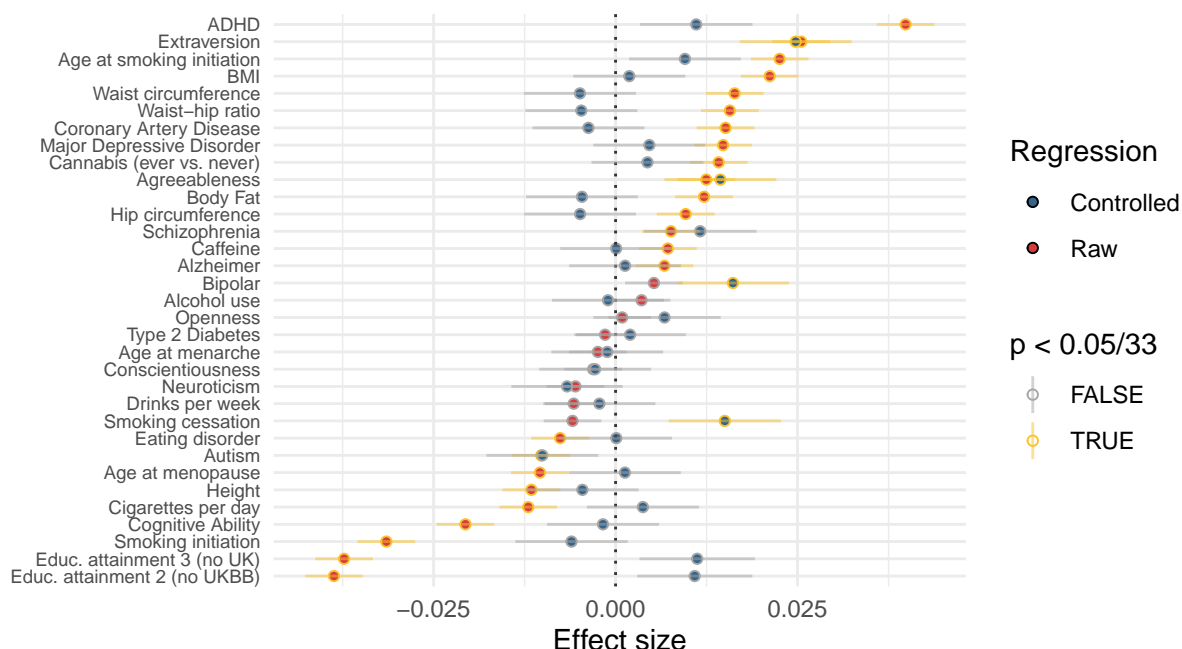


Figure 16: Selection effects controlling for earnings in first job (estimated by mean earnings from ASHE 2007 for the SOC2000 job code) and education (left education before 16, 16-18, or after 18). Raw effects are shown for comparison. Lines are 95% confidence intervals uncorrected for multiple testing.

Genetic correlations with EA3

Another way to examine the “earnings” theory of natural selection is to compare selection effects of PGS with their genetic correlation with educational attainment (EA3). Since EA3 strongly predicts earnings, if earnings drives differences in fertility, we’d expect a correlation between the two sets of results. Figure 17 shows this is so.

TODO: ref source of data.

Causality

Different polygenic scores are correlated. Table 4 shows the top correlations in the sample. Because of this, bivariate correlations between PGS and number of children might be driven by other genetic scores. To explore which polygenic scores are driving negative selection, we run a single omnibus regression of *number of children* on all the PGS. We exclude EA2, waist-hip ratio, waist-circumference, and “Hip combined” since they are highly correlated with other scores, which could make our estimates unstable. Figure 18 shows the results. Interestingly, several PGS remain independently significant, although effect sizes are reduced.

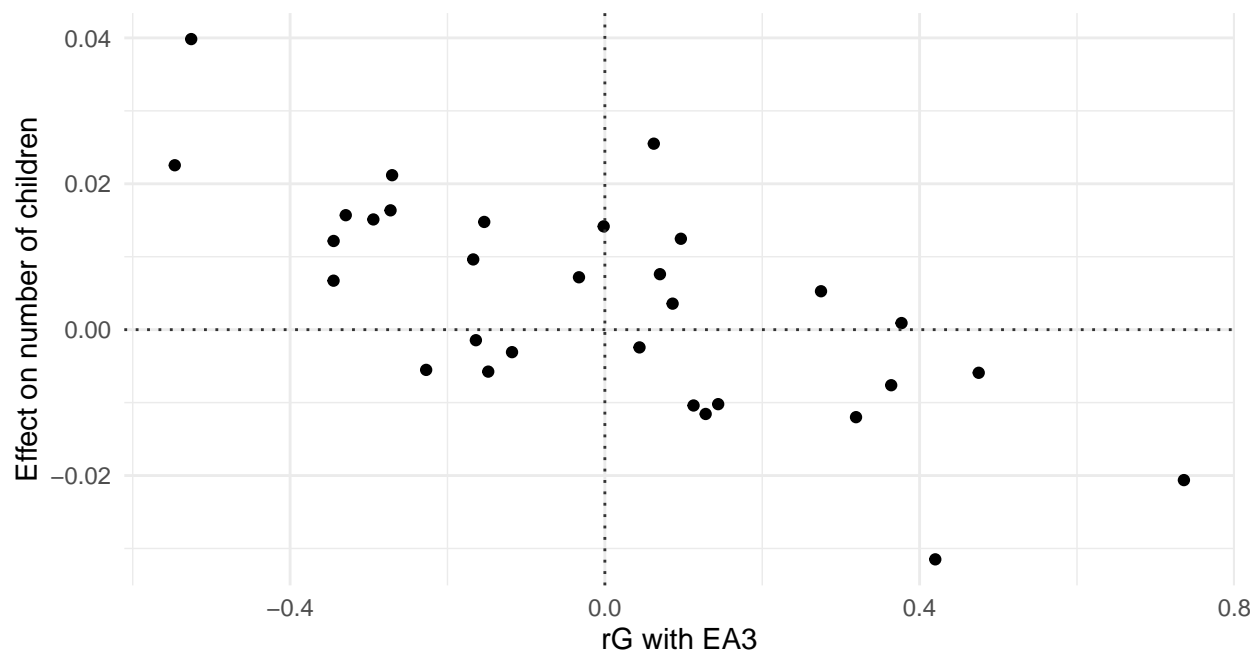


Figure 17: Selection effects plotted against genetic correlation with EA3.

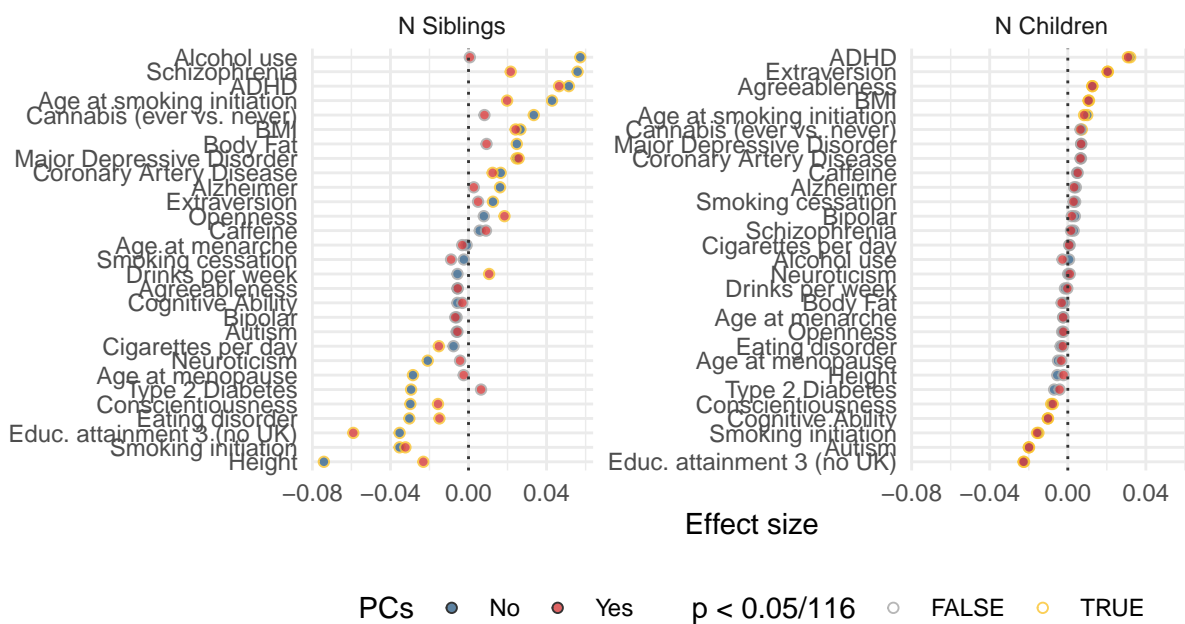


Figure 18: Partial correlations of PGS with fertility, from a single regression.

Table 4: Top 10 correlations between polygenic scores

PGS	PGS	Correlation
Educ. attainment 2 (no UKBB)	Educ. attainment 3 (no UK)	0.89
Hip circumference	Waist circumference	0.807
BMI	Waist circumference	0.753
Waist circumference	Waist-hip ratio	0.711
BMI	Hip circumference	0.697
Body Fat	Waist circumference	0.435
BMI	Body Fat	0.425
BMI	Waist-hip ratio	0.425
Body Fat	Hip circumference	0.385
ADHD	Autism	0.328

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