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Intrauterine Growth and Intelligence Within Sibling Pairs: Findings From the Aberdeen Children of the 1950s Cohort

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ABSTRACT

OBJECTIVE. The objective of this study was to examine whether the established positive association between birth weight and childhood psychometric intelligence is seen within singleton sibling pairs from the same family as well as between nonsiblings.

METHODS. We examined the association of intrauterine growth (measured as birth weight standardized for gender and gestational age) with psychometric intelligence (measured using the Moray House picture test) at 7 years old in a birth cohort of 9792 individuals who were singleton births occurring in Aberdeen, Scotland, between 1950 and 1956. We further compared this association within siblings with that between nonsiblings in the cohort; this family-based analysis included 1645 sibling pairs (N = 3290 individuals).

RESULTS. There was a positive linear association between birth weight and childhood psychometric intelligence at age 7 in the whole cohort, which remained with adjustment for a range of potential confounding factors. A one standard deviation increase in birth weight for gestational age z score was associated with a greater intelligence score in a regression model adjusting for sex, year of birth, paternal social class, maternal height, age, gravidity, and birth outside of marriage. The mean age difference between the siblings within each family pair was 2.2 years. In the family-based analysis there was no strong association between birth weight for gestation age z score and intelligence within sibling pairs from the same family, but there was a positive association between nonsiblings; the difference in these effects being unlikely to be due to chance. With additional adjustment for social class, maternal height, age, gravidity, and birth outside of marriage, the within-sibling pair effect was unaltered and the nonsibling effect attenuated, although an apparently robust positive association remained. In these adjusted analyses there was still evidence that the within-sibling effect differed from that between nonsiblings.
We found no evidence that the main effects or the family-based analyses differed between males and females.

**DISCUSSION.** Our family-based analyses are consistent with one previous large family-based study that included >2500 sibling pairs and found no within-sibling-pairs association between birth weight and childhood intelligence, but did not make a direct statistical comparison between the within-sibling-pairs association and that between nonsiblings. In a second large study that included only sibling pairs of the same sex, in males there was a within-sibling-pairs association between birth weight and childhood intelligence. However, for females there was no within-sibling-pairs association. The authors commented that this sex difference was puzzling and needed replication. Although we had less power than this earlier study to assess sex differences, the point estimates and statistical tests in our study suggested that there was no sex difference.

**CONCLUSIONS.** The lack of any association within sibling pairs from the same family suggests that the association between birth weight and childhood intelligence in the general population of singletons is largely explained by fixed family factors that are closely matched in siblings of a similar age. These factors include family socioeconomic characteristics, parental education and intelligence, genetic factors and fixed maternal factors, such as her behaviors, size, and metabolic and cardiovascular health that are constant from one pregnancy to the next and could therefore affect her offspring growth and intelligence across all pregnancies.

**Birth weight** is positively associated with psychometric intelligence in later life, but the mechanisms for this association are unclear. A range of family characteristics, including genetic factors, but also socioeconomic position, maternal behavior and health, and parental intelligence and education, will affect both intrauterine growth and offspring intelligence and could therefore explain any association between the 2. Within-sibling analyses provide a powerful approach to controlling for a range of fixed familial and parental characteristics that are shared by siblings of a similar age, and in this respect, they are complementary to conventional multivariable approaches in observational studies in which many of these factors are either not measured or are inaccurately measured. Although these sibling analyses cannot distinguish completely between genetic or nongenetic mechanisms for any association observed, they have the advantage over twin studies of being generalizable to the majority of the population who are singletons and can be used to determine if maternal and family factors that are shared by siblings explain any of the association between birth weight and intelligence. To our knowledge, 3 published studies have used within-sibling analyses to address this issue. The 2 largest studies to date (one including 2521 sibling pairs and the second including 1683 pairs) have reported contradictory results. In 1 study, there was no association between birth weight and intelligence within siblings, and the authors concluded that socioeconomic position explained the association between birth weight and intelligence. Although as discussed previously in this article, the lack of an association within siblings could be explained by a range of family factors in addition to socioeconomic position. By contrast, in the second large study, a positive within-sibling association was found for boys, although not for girls, and the authors concluded that, at least for boys, the association was not explained by socioeconomic position or other fixed family factors. In a more recent study that included just 235 sibling pairs, a positive within-sibling association was reported for both genders. Thus, to date, there is limited and contradictory evidence from within-sibling analyses concerned with the association of fetal growth and offspring intelligence.

The aim of this study was to compare the magnitude of the association between birth weight for gestational age and intelligence measured at 7 years old within siblings to the same association between nonsiblings in a birth cohort study that includes 1645 sibling pairs.

**METHODS**

Data from the Aberdeen Children of the 1950s cohort study were used. This consists of 12,150 children who were born in Aberdeen between 1950 and 1956 for whom comprehensive information was abstracted from the Aberdeen Maternity Neonatal Databank about the course of their mother’s pregnancy and the children’s physical characteristics at birth and linked to their school records, including standard tests of psychometric intelligence that were administered to all primary school children in the 1960s in Scotland at ages 7, 9, and 11. In this study, we only included participants from singleton births.

We first examined the association of birth weight with childhood intelligence in the whole cohort (referred to as the “whole-cohort analysis” for the remainder of the article). This enabled us to confirm the well-established positive association between birth weight for gestational age and intelligence in this cohort and also to examine the effect on the association of adjustment for potential confounding factors so that we could compare our conclusions based on this analysis with that obtained from the family-based analyses. This whole-cohort analysis was conducted on the 9792 (81%) singleton births (N = 316 individuals removed from the analysis because they were a multiple birth) who had complete data on intelligence test scores and all other covariates (N = 2042 removed because of some missing data). The dis-
tributions of age, gender, birth weight, and intelligence did not differ between those excluded because of missing data and those included in the analyses (all \( P > .4 \)). The family-based analyses (referred to as the “family-based analysis” for the remainder of the article), in which we compared the magnitude of the association between birth weight and intelligence within siblings with the magnitude of this association between nonsiblings, were conducted on a group nested within the 9792 participants of the main analysis. To be included in this family-based analysis, a participant had to have at least 1 other sibling within the cohort who was also a singleton birth and had complete data on all covariates included in any model. These family-based analyses were undertaken on 1645 sibling pairs (3290 individuals).

The intelligence test scores for the 3 ages were strongly correlated with each other, and the associations that we examined did not differ substantially if we used intelligence test scores measured at any of 3 ages (7, 9, and 11) and so only results for the tests conducted at 7 years old are reported. The tests used at age 7 were the Moray House Picture Intelligence test numbers 1 or 2.\(^{15}\) The Moray House tests are a large series of mental tests devised by Thomson, Principal of Moray House College of Education (in Edinburgh), and his associates in the 1930s that are administered to groups of children and have been used throughout Scotland in educational settings and for the Scottish Mental Surveys of 1932 and 1947.\(^ {16,17}\) The tests include a number of “verbal reasoning” tests (eg, identifying the odd one out in pictures or matching pictures) and also some numeric and spatial reasoning items. The tests have high levels of test-retest reliability.\(^ {16}\) To our knowledge, they have not been formally compared with more commonly used tests of childhood intelligence such as Raven’s progressive matrices\(^ {18}\) or Wechsler’s intelligence scales,\(^ {19}\) but a number of “verbal reasoning” tests (eg, identifying the odd one out in pictures or matching pictures) and also some numeric and spatial reasoning items. The tests have high levels of test-retest reliability.\(^ {16}\) To our knowledge, they have not been formally compared with more commonly used tests of childhood intelligence such as Raven’s progressive matrices\(^ {18}\) or Wechsler’s intelligence scales,\(^ {19}\) but a number of studies demonstrate that they predict a range of outcomes, including educational attainment and adult socioeconomic position, with magnitudes that are similar to those of other tests of childhood intelligence.\(^ {17}\) The intelligence tests were taken within 6 months of the child’s seventh birthday. Tests were age-standardized with means of 100 and SDs of 15 for Scotland as a whole.

Birth weight, gestational age, whether the child was born outside of marriage, paternal occupation at the time of birth and maternal gravity (number of pregnancies), height at the time of her pregnancy (nearest inch—mean of measurement at the 2 pregnancies were used in the sibling pairs analyses) and age at the birth of the child were abstracted from Aberdeen Maternal and Neonatal Database, which collected these data during the antenatal and perinatal period using research standard protocols.\(^ {15}\) The participants’ intrauterine growth rate was estimated by calculating internally standardized gender and gestational age (in completed weeks) \( z \) (SD) scores. The father’s occupation at birth was classified according to the 1950 Registrar General’s classification.\(^ {20}\)

**Statistical Methods**

**Whole-Cohort Analyses**

We undertook a series of multivariable linear regression models to assess the association of birth weight with childhood intelligence in the whole cohort. In the basic model, adjustment was made for gender and birth year only. Additional adjustment was then made for father’s occupational social class at birth (5-level categorical variable: I and II, III nonmanual, III manual, IV, V), maternal gravida (4-level categorical variable: 1, 2, 3, \( \geq 4 \)), maternal height (continuous variable in inches), paternal age at the birth of her child (5-level categorical variable: 15–19, 20–24, 25–29, 30–34, 35 or older), and birth outside of marriage (binary variable). In these models, robust standard errors, taking account of nonindependence between siblings within the sample, were used to estimate all standard errors and \( P \) values.

**Family-Based Analyses**

The general model for simultaneously estimating the within-sibling and the between-nonsiblings association of birth weight and childhood intelligence can be expressed as follows:

\[
e(Y_i) = \beta_0 + \beta_w(X_w - X_i) + \beta_X X_i
\]

where \( Y_i \) represents an individual’s intelligence test score, \( X_w \) the individual’s birth weight, and \( X_i \) the mean birth weight for a pair of siblings. The within-pair coefficient \( \beta_w \) gives the change in intelligence for a one-unit change in the difference between the individual birth weight and the sibling pair average while holding the latter constant (that is, the effect of birth weight on intelligence when matching on factors that are shared by siblings). The between-nonsiblings coefficient \( \beta_X \) gives the expected value of intelligence for a one-unit change in the average birth weight of a pair of siblings while holding the individual variation from this average constant (that is, it assesses the association of birth weight with intelligence between nonsiblings by providing the mean difference in intelligence for a unit change in sibling [family] average birth weight).

The 9792 singleton births that had complete data on all variables included in these analyses belonged to 7688 families; 3922 participants had at least 1 sibling within the cohort. Although 801 participants were part of a group of \( \geq 3 \) siblings, it can be seen from the previous equation that it would be inappropriate to include groups of differing sizes in the analysis because the larger the group, the less error there would be in the estimate of \( \beta_w \). Therefore, for groups with \( \geq 3 \) siblings, we randomly selected 2 siblings to be included in the analysis. This resulted in 1645 sibling pairs (3290 individuals) with both siblings being singleton births and having
those studies. Therefore allows direct comparison of our results with the main results. However, to make direct comparisons with the study by Matte et al\textsuperscript{13} that reported a within-sibling effect in male-only sibling pairs, but not in females, we also examined and compared within-sibling and between-nonsibling effects for same-gender sibling pairs.

### RESULTS

Table 1 shows participant characteristics for the 9792 participants included in the whole-cohort analysis and the 3290 (1645 pairs) cohort members who were nested in the whole cohort and included in the family-based analyses.

#### Whole-Cohort Analysis

In the whole cohort, there was a positive linear association between birth weight and childhood intelligence (Fig 1). A 1-SD increase in birth weight for gestational age \( z \) score was associated with a 1.54 (95% confidence interval [CI]: 1.21 to 1.87; \( P < .001 \)) greater intelligence score in a regression model adjusting for gender and year of birth. With additional adjustment for paternal social class, maternal height, age, gravidity, and birth outside of marriage, this attenuated to 0.99 (95% CI: 0.67 to 1.32; \( P < .001 \)), but a positive association remained. In the fully adjusted model, including adjustment for gender and gestational age, a 1-kg greater birth weight was associated with a 3.16 (95% CI: 2.50 to 3.82; \( P < .001 \)) greater intelligence score.

#### Family-Based Analysis

The mean age difference between the sibling pairs was 2.2 (SD: 1.2) years. Differences between maternal age at birth (mean: 2.2 years), gravidity, and sibling birth order (both in agreement with each other) were consistent with what one would expect for siblings to the same mother. There were high levels of absolute agreement on father’s occupational social class and whether the birth was outside of marriage for each pair of siblings (Table 2). Siblings were also frequently concordant for whether or not they had been born preterm. Birth weight was strongly correlated within 2 siblings, as was childhood intelligence, with a modest correlation within siblings for gestational age (Table 2). Fifty percent (817 pairs: 439 both male and 378 both female) of the sibling pairs were the same gender and 50% (828 pairs) included 1 boy and 1 girl.

Table 3 shows the associations of birth weight for gestational age with intelligence scores at age 7 within siblings and between nonsiblings. In the basic model, there was no association between birth weight for gestational age \( z \) score and intelligence test scores at age 7 within sibling pairs, whereas there was a positive association between nonsiblings. With adjustment for potential confounders, a 1-SD increase in birth weight for gestational age \( z \) score was associated with a 1.54 (95% CI: 1.21 to 1.87; \( P < .001 \)) greater intelligence score in a regression model adjusting for gender and year of birth.
tial covariates, the coefficient for the within-siblings analysis remained largely unchanged, which one would anticipate because most of the covariates are known to be fixed within siblings (such as maternal height and parental background education and socioeconomic position) or are correlated. The association between nonsiblings was attenuated with adjustment, but an apparently robust positive association remained. In both the basic model and the one with adjustment for potential confounding factors, there was statistical evidence that the association within siblings differed from that between nonsiblings.

There were 439 pairs (878 individuals) in which both siblings were male and 378 (756 individuals) in which both were female. Although less precise than for the analyses including all sibling-pairs and with both genders combined, the family-based analyses were essentially the same when we repeated them in single-gender sibling pairs only and stratified by gender; in the basic model for males, the within-sibling effect was 0.55 (95% CI: −0.63 to 1.73) and the between-nonsibling effect was 1.71 (95% CI: 0.68 to 2.75; \(P\) for difference in effect estimates = .16); equivalent results for female-only sibling pairs were 0.40 (95% CI: −0.68 to 1.47) and 2.57 (95% CI: 1.49 to 3.65; \(P\) for difference in effect estimates = .01).

When we repeated the family-based analyses with exclusion of the 160 sibling pairs that included at least 1 sibling who had been born preterm (<37 weeks’ gestation), the results were less precise but did not substantially differ from those presented in Table 3. Similarly, when we removed the 99 sibling pairs that included at least 1 sibling who was born with a low birth weight (<2500 g), the results did not substantively differ from those presented in Table 3.

When we examined the effect of a binary variable—small for gestational age (defined as birth weight for gestational age below the 10th percentile) on intelligence—there was no within-sibling pair effect (mean difference in intelligence comparing those who were small for gestational age with those who were not with adjustment for potential covariates like in the adjusted model in Table 3 within siblings: 0.87 [95% CI: 0.30 to 1.31]), but there was a between-nonsibling effect (equivalent adjusted effect between nonsiblings: −4.14

### Table 2: Comparisons Between 2 Siblings in the Aberdeen Children of the 1950s Cohort Study (N = 1645 Sibling Pairs [3290 Individuals])

<table>
<thead>
<tr>
<th>Variable</th>
<th>Continuous Variables</th>
<th>Correlation (P)</th>
<th>(\kappa) Score (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birth weight, g</td>
<td>68 (463)</td>
<td>0.56 (&lt;.001)</td>
<td>0.25 (&lt;.001)</td>
</tr>
<tr>
<td>Gestational age, wk(^a)</td>
<td>0 (−1, 1)</td>
<td>0.40 (&lt;.001)</td>
<td>0.66 (&lt;.001)</td>
</tr>
<tr>
<td>Intelligence score at age 7 y</td>
<td>0.9 (15.6)</td>
<td>0.57 (&lt;.001)</td>
<td>0.82 (&lt;.001)</td>
</tr>
<tr>
<td>Preterm birth</td>
<td>86</td>
<td></td>
<td>0.64 (&lt;.001)</td>
</tr>
<tr>
<td>Social class at birth in 6 categories</td>
<td>76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Social class at birth in 2 categories (manual vs nonmanual)</td>
<td>95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Born outside of marriage</td>
<td>99</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) For gestational age, the difference between siblings is given as median and interquartile range, and the correlation coefficient is Spearman’s rank correlation (for others, Pearson’s correlation coefficient is estimated).
other studies in this area. They suggest that the association between birth weight for gestational age and intelligence among siblings pairs: 0.34 [95% CI: 0.04 to 0.64]) and between nonsiblings (0.91 [95% CI: 0.61 to 1.22]) effects, but again, statistical evidence of a weaker within-sibling effect compared with that between nonsiblings (P for difference between the 2 effects = .004). When we considered gestational age as a continuum, there were both within-sibling (adjusted difference in intelligence per week of gestational age 0.34 [95% CI: 0.04 to 0.64]) and between-nonsibling (0.91 [95% CI: 0.61 to 1.22]) effects, but again, statistical evidence of a weaker within-sibling effect compared with that between nonsiblings (P = .001 for difference in effect).

DISCUSSION

In the cohort as a whole, our results suggest a modest positive association (equivalent to a 3-point greater intelligence test score for each 1-kg greater birth weight) between birth weight for gestational age and intelligence that remained even with adjustment for socioeconomic position and other family and maternal characteristics. These findings are consistent with an earlier report from this study that analyzed a slightly different subset of the full cohort and was concerned with determining the relative impact of a range of early life characteristics on childhood intelligence. These whole-cohort analyses, in which we formally compared a within-sibling pair effect to an effect between nonsiblings, advance our understanding of this association. They suggest that the association between birth weight for gestational age and intelligence among singletons is largely explained by characteristics that are the same for siblings, because there is little evidence of an association within siblings. Our family-based analyses are consistent with 1 previous large family-based study that included over 2500 sibling pairs and found no within-sibling association between birth weight and childhood intelligence. In a second large study that included only sibling pairs of the same gender in males (N = 812 pairs), there was a within-sibling association between birth weight and childhood intelligence. However, for girls (N = 871 pairs), there was no within-sibling association. With respect to this gender difference, the authors concluded that “the difference between boys and girls is puzzling and needs replication.” Although we had less power than the study by Matte et al to assess gender differences, the point estimates and statistical tests in our study suggested that there was no gender difference. Instead, they confirmed that for both males and females, there was no association between birth weight and intelligence once there was matching on characteristics that were fixed for siblings.

One other sibling study using data from the US Panel of Income Dynamics and involving 581 families found a within-sibling effect for the association of low birth weight with educational attainment: discordance of low birth weight (defined as <2500 g) within siblings was associated with a 74% (odds ratio: 0.26, no CIs or SEs provided) reduction in the odds of graduation from high school by 19 years old. The authors concluded that this provided robust evidence of an unconfounded association between birth weight and educational achievement. Although educational attainment is related to psychometric intelligence, the 2 are different because educational attainment will be influenced by a wide range of factors that affect access to and quality of education in addition to reflecting intelligence. Thus, it is difficult to compare the results of this study with ours because birth weight versus birth weight for gestational age as a continuous variable) differ importantly between the 2 studies.

TABLE 3 Within- and Between-Siblings Association of Birth Weight With Childhood Intelligence Test Scores (N = 3290 Individuals, 1645 Sibling Pairs)

<table>
<thead>
<tr>
<th>Mean Difference in IQ Score per 1 SD of Gestational Age and Gender-Standardized Birth Weight (95% CI)</th>
<th>P&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Within Siblings</strong></td>
<td><strong>Between Siblings</strong></td>
</tr>
<tr>
<td>Basic model</td>
<td>0.50 (−0.25 to 1.26)</td>
</tr>
<tr>
<td>Adjusted model</td>
<td>0.49 (−0.26 to 1.26)</td>
</tr>
</tbody>
</table>

* Adjusting for gender and year of birth.
* As in the basic model plus adjustment for the father’s occupational social class, maternal age, maternal height, gravidity, and whether the child was born outside of marriage.
* The P value is testing for statistical evidence of a difference in effect comparing within- and between-sibling coefficients.
What Family-Based Factors Might Explain the Association Between Birth Weight and Childhood Intelligence?

Taking the totality of evidence (2 [ours and 1 previous] large null within-sibling studies and 1 large study that shows a within-sibling effect only for the subgroup of males), it seems that the association between birth weight and childhood intelligence seen in general populations of singletons is largely explained by factors that are shared by siblings. The interpretation of a lack of association within sibling pairs has in other papers been taken to indicate that the association in the general population of singletons is the result of confounding by parental socioeconomic position. However, several other factors that are identical or very similar between siblings are also likely to be important in explaining these results. In the U.S. National Longitudinal Survey of Youth, the association between family poverty (income below the official poverty line) and childhood intelligence was completely mediated by 4 latent variables representing “cognitive stimulation in the home,” “parenting style,” “physical environment in the home,” and “poor child health at birth.” Although parenting style, cognitive stimulation, and the physical environment in the home cannot directly affect birth weight, they are likely to reflect broader parental attributes such as their intelligence, educational attainment, and interaction with their offspring, which will also reflect maternal behaviors during pregnancy and hence could affect offspring birth weight. Maternal smoking during pregnancy may be particularly important here because this is clearly related to low birth weight and has been shown in a number of studies to be associated with low offspring psychometric intelligence.

Parental intelligence and education may also affect both birth weight (through behaviors such as smoking and alcohol consumption during pregnancy) and childhood intelligence through other postnatal behaviors such as breast feeding, which is positively related to childhood intelligence, and also through genetic factors that link parental and offspring intelligence. However, siblings share 50% of their genetic material on average and therefore within-sibling analyses do not provide strong control for shared genes. Three within-twin pair studies have attempted to determine if the relationship between birth weight and intelligence is primarily driven by genetic or environmental factors, but these are difficult to interpret. In the largest twin study to date, there was no association within monozygotic twin pairs (N = 81), leading the authors to suggest that genetic factors explained the association. However, 2 other studies of 257 and 276 monozygotic twin pairs found that within-twin pairs’ birth weight differences were positively associated with intelligence differences. The small sample sizes of these studies mean that all estimates were imprecise and, although reported in ways that would suggest that the results were inconsistent, an inspection of the 95% CIs suggests that there is no heterogeneity between them, with all point estimates suggesting modest positive effects within monozygotic twins. Moreover, as suggested elsewhere, twin studies of this sort are subject to the largely unquantifiable bias that results from it being difficult to be certain that the correct birth weight in same-sex twins is associated with each twin in childhood or adult life.

It is important to note that the relevance of findings from twin studies to explaining associations in the general population is unclear because important differences exist between twins and singletons in their intrauterine growth trajectories and also in their intelligence. Of relevance here, in a separate analyses of the Aberdeen Children of the 1950s cohort, we have shown that within families, twins have on average lower intelligence test scores than their singleton siblings. In that study, adjustment for birth weight and gestational age attenuated the lower intelligence of the twins compared with their singleton siblings. Taking those results together with our results presented here, it seems that the lower intelligence of twins compared with singletons is not explained solely by fixed family characteristics, but is, at least in part, explained by intrauterine factors that affect birth weight and gestational age and that vary between a twin and singleton pregnancy to the same mother. By contrast within the general population of singletons, the modest association between birth weight for gestational age and intelligence seems to be largely explained by fixed family characteristics. These findings are consistent with the growing evidence that the differences in intrauterine growth between twins and singletons are driven by different factors from those that drive the variation in intrauterine growth among singletons. The reduced growth of twins relative to singletons is largely explained by in utero constraints, whereas variation in growth between singletons is explained by this as well as a much wider range of factors, including infection, complications of pregnancy, and fixed maternal factors.

Finally, the lack of a within-sibling pair effect could be explained by relatively stable maternal health characteristics such as her size and metabolic and cardiovascular health that affect both perinatal growth and the intelligence of all her offspring. Our results provide little support for the hypothesis that variations in the adequacy of fetal nutrition and placentation that may vary from one pregnancy to the next in the same mother explains the association between birth weight and intelligence within singletons.

The association between preterm birth and low childhood intelligence is a robust finding from a number of studies. We found an association of preterm birth and lower intelligence, and a positive association of gestational age, treated as a continuous risk factor, with childhood intelligence both within siblings and between non-
siblings, but the within-sibling association was weaker than that between nonsiblings. This finding suggests that among singletons, the association of preterm birth or lower gestational age with lower intelligence is also importantly driven by factors that are shared by siblings. Our main results, concerning the effect of intrauterine growth rate (measured by birth weight for gestational age), were not driven by effects of preterm birth or low birth weight because they were robust to the removal of individuals who were born preterm and those who were born weighing <2500 g.

Study Strengths and Limitations
Our study adds to the scant and inconsistent evidence using family-based analyses to explore the relationship between birth weight and childhood psychometric intelligence. We know from the sampling structure and linkage to maternity records that all of the siblings had the same biologic mother and were still living in the same household as each other at the time of their first recruitment in primary school. However, we do not have information on whether the siblings had the same biologic father. Given that <1% of the participants included in this analysis were born outside of marriage and most siblings were born within 2 years of each other, it is likely that the majority had the same biologic father. Nonetheless, we cannot be certain whether or not we are matching on fixed paternal factors in our within-sibling analysis.

Our study is of children born in the 1950s and its relevance to contemporary children may be questioned. The association between birth weight and childhood intelligence that we found in the whole cohort was of a similar magnitude to that found in other cohorts, including those of children born in more recent decades, with a 1-kg greater birth weight being associated with on average a 2- to 3-point greater intelligence test score. Of the previous within-sibling studies to assess this association, that by Record et al, whose results were consistent with ours, was conducted in a cohort born in the 1930s, that by Matte et al, which found a within-sibling effect in males only, was conducted in a cohort born in the late 1950s/early 1960s, and the smallest study to date, which reported within-sibling associations in both genders was conducted in a cohort born in the mid-1980s in Australia. It is possible that the explanation for this association has changed over time, and that in more contemporary cohorts, the association between birth weight and intelligence is not largely driven by factors that are shared within families. However, large family-based studies in contemporary populations would be required to replicate the findings in the small 1980s study before one could feel confident that this was the case.

We do not have information on some potential covariates such as maternal smoking and alcohol consumption during pregnancy, parental education or intelligence, infant feeding practice, family environment, or school-based factors. We had just 1 measure of childhood socioeconomic position (father’s occupational based social class at birth), which is likely to be inadequate to capture the full confounding effect of socioeconomic position. However, the within-sibling analyses have the advantage over the conventional multivariable approach in that it is able to control for a large range of unmeasured covariates or covariates that may have been measured inaccurately that are identical or very similar for siblings. Very few observational studies will have accurate measures of all characteristics that might explain the association between birth weight and psychometric intelligence. On the other hand, although the family-based study has this advantage over conventional observational studies that do not include families, it takes us just 1 step further in our understanding. Thus, our results point to family-based characteristics as explaining the association between birth weight and childhood intelligence; additional detailed research within families is required to determine which of the possible mechanisms described here might be most important.

CONCLUSIONS
We have confirmed findings from previous studies that there is a modest positive association between birth weight for gestational age and childhood psychometric intelligence. Our within-sibling analysis suggests that the association between birth weight for gestational age and intelligence in singletons is explained by factors that are similar for singleton siblings. These factors include family socioeconomic characteristics, parental education and intelligence, genetic factors, and fixed maternal factors such as her behaviors, size, and metabolic and cardiovascular health that could affect her offspring growth and intelligence across all pregnancies.

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