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METHODOLOGY

Sibling configuration and childhood growth in contemporary British families

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Background Life history theory and resource dilution models of the family suggest that siblings may present a threat to healthy development because they compete for resources that parents have available to invest in individual offspring. Using data from a large cohort study of contemporary British families (ALSPAC), we test this hypothesis using childhood growth trajectories as a biomarker for health status.

Methods Incorporating time-varying measures of changing family structure and socio-economic environment, this study represents the first true longitudinal analysis of family configuration effects on human growth. Using separate multi-variate multi-level models we estimate the effect of sibling number and sibling age and sex on height from birth to 10 years.

Results Adjusting for family level socio-economic factors, the presence of siblings is associated with deficits in height across the study period. At the largest comparison, we estimate that compared with only children, children with four siblings have a reduced birth length by −8.7 mm (95% confidence interval (CI): −14.8 to −2.6) and a reduced rate of growth by −2.3 mm per year (95% CI: −3.8 to −0.8), leading to a deficit of 31.5 mm by age 10. Older siblings are associated with larger lasting negative consequences on height than younger siblings. We find no difference in the height of children in relation to the sex of siblings.

Conclusions Even in the relatively wealthy, well-nourished conditions of modern Western society, children are not buffered from the health costs of reduced parental investment. Later-born children appear worst affected by within family resource division.

Keywords Height, siblings, ALSPAC, life history theory, resource dilution

All other things being equal, siblings dictate a division of finite parental resources, leading to lower individual shares per offspring, negative development outcomes and ultimately lower Darwinian fitness. This is the central premise of the evolutionary life history approach to family size that has stimulated a wealth of studies in animal behavioural ecology.[1,2] An extensive literature on the experimental manipulation of clutch size in both birds and small mammals demonstrates strong evidence of negative relationships between sibling number and individual health, survival and fertility.[1,2] Observational studies of traditional and historical human societies by human behavioural ecologists have suggested similar relationships.[3–9]

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Comparable research amongst contemporary Western societies has focused on educational progress or other markers of intelligence, and negative effects of sibling number have been demonstrated across a range of cross-sectional studies in the United States, Europe and Asia.[10,11] Such tests have typically been framed in terms of resource dilution theory,[11,12] a perspective virtually identical to evolutionary models apart from its agnosticism in relation to ultimate fitness effects. Relatively little directed study has focused on siblings as determinants of physical development or health outcomes. Here, we present an analysis of sibling configuration effects on the growth trajectories of contemporary British children. Height is a widely accepted biomarker for health status determined by genetic potential and the balance between nutrition and environmental demands such as disease, particularly in early life.[13] Explicitly testing a resource dilution model, we hypothesize that the presence of siblings will be associated with deficits in height across childhood. Assuming that parental resources are divided following a $1/x$ function, where $x =$ number of offspring,[11] we further predict that the costs associated with additional siblings will decline in magnitude as number of siblings increase (i.e. the difference between 1 and a 1/2 is greater than the difference between 1/2 and 1/3 and so on).

Using detailed longitudinal data on growth from the Avon Longitudinal Study of Parents and Children (ALSPAC), sibling effects are estimated using a multivariate multi-level modelling strategy.[14] We explore the determinants of individual growth using a large range of time-varying covariates relating to changing family configuration and parental resources (see Materials and methods). As such our study presents significant methodological advancement over prior literature to consider family size effects. Cross-sectional designs dominate past research which has focused on height at a particular age[15,16] or measured growth with repeated measurements without consideration of temporal changes in the family environment.[17] These limitations may lead to spurious associations as parental resource wealth or wider aspects of family configuration (e.g. father presence) can vary across time, often in direct association with the addition of children.[18,19] Furthermore, sibling number is itself a time-varying measure and past study designs have not taken into account that individuals may experience a range of sibling configurations over their life course. These points are not trivial and have led to notable controversy in the educational and IQ related literature,[10,20] as subtle longitudinal and sibling pair methods have not always supported popular conclusions.[21,22]

We also extend the scope of previous studies to consider the role of relative age and sex of sibships. A resource dilution perspective predicts that older siblings will be relatively more costly because, given their existence prior to the birth of the study child, they consume parental resources for a longer time than younger siblings.[23] A recent large sample Norwegian study of IQ examining relations within families found significant advantages to early-born children consistent with this model.[24,25] We are aware of no comparable studies to consider the role of birth order in health outcomes. Varying patterns of sex-biased parental investment have been documented across human cultures. Evidence from studies of marital stability[19] and labour dynamics[18] indicates that contemporary Western societies are probably best characterized by a modest bias towards investment in male offspring.[26] Sons are also known to more energetically expensive to produce in utero, both growing faster and being larger at birth.[27–29] Such pre- and post-natal biases predict a relatively higher cost to male over female siblings.

Materials and methods

Study sample

ALSPAC is a uniquely detailed ongoing cohort study designed to examine environmental and genetic influences on the health and development of British children.[30] Study recruitment started in pregnancy, enrolling women who had an expected delivery date between April 1991 and December 1992 from the three main Bristol-based health districts of the former county of Avon. Avon has a predominantly white population, a mixture of rural and urban communities and a socio-economic mix similar to the rest of the UK. There were 14 062 live births amongst the recruited mothers. ALSPAC data are collected up to three times a year, mainly through self-completion of postal questionnaires, but also extraction from clinical records and direct examination of children at research clinics.

Our study utilized all relevant data available until questionnaires aimed at assessing children at 10 years. A number of exclusion criteria define our study sample. Children from multiple births, children recorded as dying or experiencing sibling death, and children living with other children unrelated to either the mother or her current partner (e.g. foster or adopted children) over the study period were all excluded. Cases where the child's live-in 'mother figure' is ever recorded as other than the biological mother, as absent or in a lesbian relationship were also excluded. Cases of biological father absence after birth were included, but cases where the mother is recorded as in a relationship with someone other than the biological father at pregnancy were excluded. After implementing these criteria our total study sample contained 13 176 children, each belonging to different families.

Height measurements

Birth length was extracted from medical records and height further measured to the nearest millimetre by ALSPAC staff at several points over the study period, principally at focus clinics attended by children. The latest of these measured height at a mean age of 9.9 years on 7238 children. Additional height data are provided by self-reports in questionnaires distributed to the mother. In total 88 195 measurements of height are available for 12 957 individuals.

Independent variables

Independent variables relating to family configuration, socio-economic profile and social support are distributed at various points over the study period (Table 1). Core data on family configuration were collected at six unevenly spaced 'key points' in mother-based questionnaires from birth to a child age of 10 years. Fathers are coded as present provided the mother states the child has a biological live-in 'father-figure' at the time of the questionnaire. In cases where the father is coded as absent the mothers are either coded as alone or as with a new live-in partner. This data does not distinguish between different partners of the mother subsequent to the biological father of the study child. Data on the number, residence and relatedness of children of the mother and her current live-in partner was then used to the code number of siblings of the study child which, for the purpose of this study, we define as maternally related siblings (i.e. including siblings with distinct biological fathers, but excluding siblings with distinct mothers) resident with the study child. This definition objectifies siblings as those related through the child's mother and currently dependent on the study child's mother and her current partner. Non-resident maternal siblings were rare in the study sample (only 1.8% of mothers had a non-resident child in pregnancy, rising to 3.4% by the end of the study period). A significant proportion of ALSPAC mothers recorded children unrelated to themselves but related to their current partner (8.9% in pregnancy and 6.9% by the end of the study period), but only in a very small percentage of families where such children resident (1.0 and 1.1%, respectively). Collected data does not determine if non-resident children were independent or resident with other carers.

Number of older siblings is treated as a time-invariant measure in each analysis and is calculated as equal to the total number of siblings at the first key point (which took place during the mother's pregnancy). Total number of siblings and number of younger siblings are time-varying measures. Number of younger siblings at birth is zero and derived at future key points by subtracting number of older siblings from the total number of siblings. Data on the sex of siblings were collected at different times to the key point data and did not simultaneously code relatedness. However, it was possible to match across this information to the 'key points' when total number of siblings was equal, allowing the number of younger and older brothers and sisters with the same relatedness assumptions to be imputed in most cases. Number of brothers and sisters is equal across the study period.

Multiple measures of socio-economic profile are available in ALSPAC. We include mother's educational attainment as a time invariant measure coded in pregnancy. In addition we use four measures of wealth coded at multiple points over the study period—household income, home ownership, neighbourhood quality and level of financial difficulty. Multicollinearity between these socio-economic measures was not a serious issue, given the large sample size and lack of correlations over 0.5 between any two measures at the same time point.[31] Neighbourhood quality and financial difficulty were self-rated, the former on a 4-point scale, the latter on a 15-point scale derived from individual questions regarding difficulty in affording heat, rent, food, clothing and items for the child. Two time-invariant measures of social support were also incorporated, both based on questionnaires distributed to the mother at pregnancy. The social network score comprises 10 items which ascertain the quality and frequency of social contact with friends and family and ranges from 0–30. The social support score measures perceived social support from family, friends and official agencies using a set of 10 items specifically designed for the study. The item presents statements relating to emotional, financial and instrumental support, with a summed overall score also ranging between 0–30. This measure shows a strong association with the mother's emotional well-being during pregnancy.[32] Finally, we include two other independent variables: mother's self reported height and the ethnicity of the child (coded as white or non-white). Further information on all these measures, including questionnaire downloads, can be found at www.alspac.bris.ac.uk.

Data analysis

The relationship between the independent variables and height measurements (coded to the nearest month of measurement) over the study period was examined using multi-variate multi-level models for change.[14] Individuals were treated as level-two units and the timing of measures as level-one units. All analyses were carried out using *MLwiN 2.02*. Modelling data in this way requires contemporaneous data on predictor and outcome variables, a feature not strictly met by the temporal distribution of time-variant predictors included in this study (Table 1). To overcome this issue we assumed that all independent variables had equal values to the mid-points between each available coding, imputing their value at the months where height was recorded for each individual child.

We first assessed the impact of total number of siblings on growth, constructing a final multi-variate model in a series of blocks. For each independent variable, effects on height were estimated by both

Table 1 Distribution of independent variables over the study period and descriptive statistics (percentage of cases at each study wave)

	Child age (ALSPAC questionnaire code)									
	0 years 0 months (A–D)	0 years 8 months (F)	1 years 9 months (G)	2 years 9 months (H)	3 years 11 months (J)	5 years 1 months (K)	6 years 1 months (L)	7 years 1 months (M)	9 years 0 months (P)	10 years 0 months (Q)
Family configuration										
Total sibling number ($n = 12\,349$–7038)										
0	51	–	39	24	16	–	–	10	–	9
1	33	–	41	52	57	–	–	55	–	54
2	12	–	15	17	20	–	–	26	–	27
3	2.9	–	3.8	4.9	6	–	–	7	–	8
4+	1.0		1.4	1.7	1.8			1.9		2.4
Older siblings ($n = 12\,349$)										
0	51	–	–	–	–	–	–	–	–	–
1	33	–	–	–	–	–	–	–	–	–
2+	16	–	–	–	–	–	–	–	–	–
Younger siblings ($n = 13\,176$–6738)										
0	100	–	84	65	53	–	–	44	–	41
1	0	–	15	32	41	–	–	43	–	43
2+	0	–	1.5	2.8	2.9	–	–	13	–	16
Sex of study child ($n = 13\,060$)										
Male	52	–	–	–	–	–	–	–	–	–
Female	48	–	–	–	–	–	–	–	–	–
Father presence ($n = 12\,479$–9022)										
Present	97	–	93	91	88	–	–	85	–	82
Absent—mother alone	2.6	–	6	7	9	–	–	10	–	10
Absent—new partner	0	–	1.0	1.7	3.1	–	–	5.0	–	7
Mother's age at birth ($n^a = 13\,107$)										
<25	24	–	–	–	–	–	–	–	–	–
25–29	39	–	–	–	–	–	–	–	–	–
30–34	27	–	–	–	–	–	–	–	–	–
35+	10	–	–	–	–	–	–	–	–	–
Father's age at birth ($n = 10\,902$)										
<25	12	–	–	–	–	–	–	–	–	–
25–29	34	–	–	–	–	–	–	–	–	–
30–34	33	–	–	–	–	–	–	–	–	–
35+	22	–	–	–	–	–	–	–	–	–
Parental resources										
Mother's education ($n = 11\,589$)										
CSE/Vocational	30	–	–	–	–	–	–	–	–	–
O-level	35	–	–	–	–	–	–	–	–	–
A-level	23	–	–	–	–	–	–	–	–	–
Degree	13	–	–	–	–	–	–	–	–	–
Household income ($n = 8210$–7020)										
<£200 per week	–	–	–	27	24	–	–	15	–	–
£200–299 per week	–	–	–	29	27	–	–	18	–	–
£300–399 per week	–	–	–	21	22	–	–	23	–	–
£400+ per week	–	–	–	24	28	–	–	44	–	–
Home ownership ($n = 11\,789$–7129)										
Rented	24	21	19	–	–	–	–	15	–	12
Mortgaged/buying	74	77	78	–	–	–	–	81	–	82
Owned outright	2.2	2.3	2.1	–	–	–	–	5	–	7

(continued)

Table 1 Continued

	Child age (ALSPAC questionnaire code)									
	0 years 0 months (A–D)	0 years 8 months (F)	1 years 9 months (G)	2 years 9 months (H)	3 years 11 months (J)	5 years 1 months (K)	6 years 1 months (L)	7 years 1 months (M)	9 years 0 months (P)	10 years 0 months (Q)
Neighbourhood quality ($n = 11\,993$–7239)										
Poor-fairly good	59	56	55	53	–	48	–	–	–	43
Very Good	41	44	45	47	–	52	–	–	–	57
Financial difficulty score ($n = 10\,510$–7741)										
0 (Low)	–	31	33	35	–	–	–	54	–	–
1–4 (Medium)	–	40	40	37	–	–	–	35	–	–
5+ (High)	–	29	27	28	–	–	–	12	–	–
Social network score ($n = 11\,581$)										
<23 (Low)	38		–	–	–	–	–	–	–	–
23–25 (Medium)	32	–	–	–	–	–	–	–	–	–
26+ (High)	31	–	–	–	–	–	–	–	–	–
Social support score ($n = 11\,474$)										
<19 (Low)	38	–	–	–	–	–	–	–	–	–
19–22 (Medium)	30	–	–	–	–	–	–	–	–	–
23+ (High)	32	–	–	–	–	–	–	–	–	–
Ethnicity of child ($n = 11\,308$)										
White	95	–	–	–	–	–	–	–	–	–
Non–White	4.9	–	–	–	–	–	–	–	–	–
Other										
Mother's height ($n = 11\,534$)										
Short (<160 cm)	35	–	–	–	–	–	–	–	–	–
Average (160–167 cm)	29	–	–	–	–	–	–	–	–	–
Tall (>167 cm)	36	–	–	–	–	–	–	–	–	–

[a]Sample size at first and last time point available over the study period.
Note that these values refer to the sample available at each study wave. They should not be directly interpreted as evidence of change over time due to selective attrition.

a main effect term (effect on initial status) and an interaction term with child age (effect on rate of change per year). Statistical significance of each predictor term was assessed (as in standard linear regression) by dividing the regression coefficient by its standard error. All variables relating to family configuration (except variables relating to sibling sex and age) were entered in the initial block. This model was then reduced down by a backward procedure removing associations that did not reach significance at the $P < 0.05$ level, unless their removal impacted a notable change on the coefficients of sibship size. All family configuration variables maintained in the model at this stage were carried forward to final model. The second block then entered all variables relating to parental resources and was reduced down in a similar fashion. Predictor terms were maintained if $P < 0.05$ or their presence effected notable changes on any of the family configuration coefficients. Finally, maternal height coefficients were entered in the final block. Two further separate models were constructed to consider the effects of sibling age and sex configuration. The final model for total sibship size was used as a template and each model specified by replacing the predictor terms for total number of siblings with first number of older and younger siblings, and then number of brothers and sisters.

Identifying a cubic relationship between age and childhood height in our data, we include both an age^2 and age^3 function in all our models in addition to an age effect to take into account the non-linear shape of childhood growth. Each individual is therefore assigned a cubic growth curve over the study period. However, in order to keep our analyses relatively simple to compute and interpret, our modelling strategy only estimates linear deviations away from each reference category associated with each rate of change coefficient. We therefore include a cautionary note that estimated coefficients may gloss over more complex underlying non-linear patterns in childhood growth associated with the independent variables considered.

Results

Table 2 shows the univariate associations between each independent variable and childhood growth. Table 3 summarizes the final model for total number

Table 2 Univariate associations between each predictor term and childhood height in millimetres (models include constant and age terms)

	Initial status		Rate of change	
Fixed effects	Coefficient	95% CI	Coefficient	95% CI
Family configuration				
Total number of siblings (Ref: 0)				
1	−4.1	−5.0 to −3.2	−2.4	−2.8 to −2.1
2	−4.9	−6.3 to −3.6	−2.6	−3.1 to −2.2
3	−6.8	−9.3 to −4.3	−2.9	−3.7 to −2.3
4	−6.7	−11.5 to −1.9	−4.1	−5.3 to −2.9
Sex of child (Ref: Male)				
Female	−14.9	−15.7 to −14.0	0.7	0.4 to 1.0
Father presence (Ref: Present)				
Absent: Mother Alone	−4.4	−6.5 to −2.3	0.1	0.1 to 0.1
Absent: New Partner	−13.8	−19.2 to −8.4	0.7	−0.1 to 1.5
Mother's age at birth (Ref: <25)				
25–29	3.0	1.8–4.2	0.9	0.5–1.3
30–34	2.5	1.3–3.8	1.6	1.2–2.0
35+	1.5	−0.2–3.2	1.8	1.3–2.3
Father's age at birth (Ref: <25)				
25–29	1.0	−0.7–2.7	0.9	0.4–1.4
30–34	0.7	−1.1–2.4	1.4	0.9–1.9
35+	0.6	−1.2–2.4	1.5	0.9–2.1
Parental resources				
Mum's education (Ref: CSE/Voc)				
O-level	3.1	1.9–4.3	0.7	0.3–1.1
A-level	2.4	1.1–3.7	1.2	0.8–1.6
Degree	5.0	3.4–6.6	1.7	1.2–2.2
Income (Ref: <£200 per week)				
£200–299 per week	2.5	1.1–3.9	0.2	−0.2–0.6
£300–399 per week	2.4	0.9–3.9	0.8	0.4–1.2
£400+ per week	2.9	1.4–4.4	1.9	1.5–2.3
Neighbourhood quality (Ref: less than Very Good)				
Very Good	1.0	0.2–1.8	−0.2	−0.4–0.0
Home ownership (Ref: Rented)				
Mortgaged/Buying	4.9	3.8–6.0	0.1	−0.3–0.5
Owned outright	4.3	1.4–7.2	0.4	−0.3–1.1
Financial difficulty score (Ref: Low)				
Medium	0.6	−0.4–1.6	−0.7	−1.0 to −0.4
High	−0.1	−1.2–1.0	−1.4	−1.8–1.1
Social network Score (Ref: Low)				
Medium	−0.8	−0.3–1.9	0.3	0.0–0.6
High	1.4	0.2–2.6	0.3	0.0–0.6
Social support score (Ref: Low)				
Medium	1.3	0.1–2.5	0.0	−0.3–0.3
High	2.2	1.1–3.3	−0.2	−0.5–0.1
Other				
Ethnicity of child (Ref: White)				
Non-white	−4.4	−6.7 to −2.3	1.5	0.8–2.2
Mother's height in cm (continuous)	1.0	0.9–1.1	0.3	0.3–0.3

N for each comparison is based on the maximum number of cases available for each variable (Table 1).

Table 3 Final model: total number of siblings and childhood height in millimetres

	Initial status		Rate of change	
Fixed effects	Coefficient	95% CI	Coefficient	95% CI
Intercept[a]	407.6	394.1–421.1	157.7	153.5–161.9
Additional age terms				
Age^2			−25.9	−26.1 to −25.7
Age^3			1.4	1.4–1.4
Total Number of Siblings (Ref: 0)				
1	−4.4	−5.5 to −3.3	−2.3	−2.8 to −1.8
2	−5.2	−6.8 to −3.6	−2.4	−2.9 to −1.9
3	−6.4	−9.5 to −3.3	−2.4	−3.1 to −1.7
4	−8.7	−14.8 to −2.6	−2.3	−3.8 to −0.8
Sex of child (Ref: Male)				
Female	−14.7	−15.8 to −13.6	0.8	0.5–1.1
Father presence (Ref: Presence)				
Mother alone	−0.2	−2.4–2.0		
New partner	−8.9	−12.6 to −5.2		
Mother's Age at Birth (Ref: <25)				
25–29	0.1	−0.5–0.7		
30–34	0.4	−0.1–0.9		
35+	0.1	−0.5–0.7		
Mum's Education (Ref: CSE/Voc)				
O-level	−0.1	−1.4–1.6		
A-level	−1.1	−2.7–0.5		
Degree	−1.0	−2.8–0.8		
Income (Ref: <£200 per week)				
£200–299 per week			0.3	−0.1–0.7
£300–399 per week			0.6	0.2–1.0
£400+ per week			1.4	0.9–1.9
Home Ownership (Ref: Rented)				
Mortgaged/buying	1.5	0.2–2.8		
Owned outright	−0.1	−2.8–2.6		
Financial difficulty score (Ref: Low)				
Medium			−0.2	−0.5–0.1
High			−0.6	−1.0 to −0.2
Ethnicity of child (Ref: White)				
Non-white			1.8	0.9–2.7
Mother's height in cm (continuous)	0.9	0.8–1.0	0.3	0.3–0.3

Variance components and pseudo R^2 statistics	**Coefficient**	**95% CIs**	**Pseudo R^2**
Within person			
σ^2e0	1071.1	1056.5–1085.7	0.98
In initial status			
σ^2u0	255.6	237.8–273.4	0.26
In rate of change			
σ^2u1	24.1	22.6–25.6	0.14
Covariance of σ^2u0 and σ^2u1	27.7	23.9–31.5	

[a]The estimated mean value for initial status and rate of change for the group with the baseline values for every factor included in the model.
Final N – 54 075.

of siblings including 95% confidence intervals (CI). Girls were initially −14.7 mm (CI: −15.8 to −13.6, $P < 0.001$) smaller than boys, but had an elevated rate of growth by 0.8 mm a year (CI: 0.5–1.1, $P < 0.001$), leading them to close this gap significantly over time. Relative to having a biological father present, children of mothers with new partners were associated with a consistent deficit of −8.9 mm (CI: −12.6 to −5.2, $P < 0.001$) but did not differ from children of single mothers.

Socio-economic profile was an important predictor of childhood height measurements. Children in higher income families experienced an increased rate of growth, with those in the £300–399 and £400+ per week range growing 0.6 mm (CI: 0.2–1.0, $P = 0.009$) and 1.4 mm (CI: 0.9–1.9, $P < 0.001$) more per year respectively than those on <£200 per week. Children living in mortgaged compared with rented housing were consistently 1.5 mm taller (CI: 0.2–2.8 mm, $P = 0.029$) across the study period. Children of mothers who rated their level of financial difficulty as high rather than low also experienced decreased growth by −0.6 mm per year (CI: −1.0 to −0.2, $P < 0.003$). Children of taller mothers were both estimated as being born larger (0.9 mm, CI: 0.8–1.0, $P < 0.001$, for each additional centimetre in mother's height) and growing faster (0.3 mm, CI: 0.3–0.3, $P < 0.001$ more per year for each additional centimetre in mother's height). Finally, non-white children grew faster than white children by 1.8 mm per year (CI: 0.9–2.7, $P < 0.001$). In addition to these covariates, main effects of maternal age and education were retained in the final model because of their demonstrated importance in earlier blocks (data not shown). In the absence of covariates related to paternal resources, maternal age was positively associated with childhood height. While in the absence of maternal height, maternal education was positively associated with childhood height. However, in the final model the magnitude and significance level of these effects are substantially reduced (Table 3).

In the presence of these covariates, siblings were associated with significant deficits in height across the first decade of life. Compared to only children, children in large sibships had lower initial status (one sibling: −4.4 mm, CI: −5.5 to −3.3, $P < 0.001$; two siblings: −5.2 mm, CI: −6.8 to −3.6, $P < 0.001$; three siblings: −6.4 mm, CI: −9.5 to −3.3, $P < 0.001$; four siblings: −8.7 mm, CI: −14.8 to −2.6, $P = 0.005$) and relatively decreased growth per year (one sibling: −2.3 mm, CI: −2.8 to −1.8, $P < 0.001$; two siblings: −2.4 mm, CI: −2.9 to −1.9, $P < 0.001$; three siblings: −2.4 mm, CI: −3.1 to −1.7, $P < 0.001$; four siblings: −2.3 mm, CI: −3.8 to −0.8, $P = 0.002$). By age 10 then, children remaining in one child families were 27.5 mm taller than children in two child families, 29.2 mm taller than children in three child families, 30.8 mm taller than children in four child families and 31.5 mm taller than child in five child families

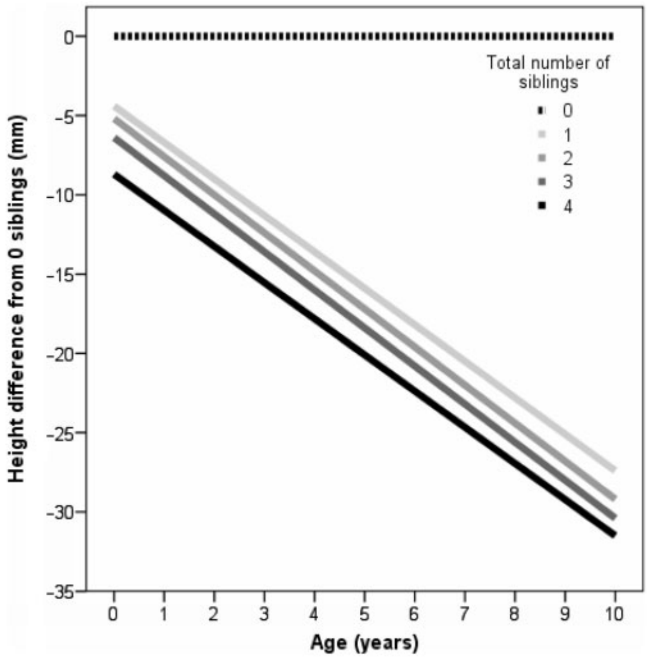

Figure 1 Total number of siblings and estimated childhood height from birth to 10 years

(Figure 1). These effect estimates meet our prediction that the cost of each additional sibling decreases as family size increases.[11] Note that unadjusted coefficient estimates using the same restricted sample are generally slightly larger than the adjusted coefficients in Table 3 for both initial status (one sibling: −4.5 mm, CI: −5.6 to −2.2, $P < 0.001$; two siblings: −5.4 mm, CI: −7.1 to −3.7, $P < 0.001$; three siblings −6.6 mm, CI: −9.8 to −3.4, $P < 0.001$; four siblings: −8.3 mm. CI: −11.5 to −2.0, $P < 0.010$) and rate of growth (one sibling: −2.3 mm, CI: −2.8 to −1.8, $P < 0.001$; two siblings: −2.5 mm, CI: −3.0 to −2.0, $P < 0.001$; three siblings: −2.7 mm, CI: −3.5 to −1.9, $P < 0.001$; four siblings: −3.0 mm, CI: −4.5 to −1.5, $P < 0.001$).

In a multi-level model for change total outcome variation is partitioned into several within and between person variance components. For each of these components a pseudo-R^2 statistic can be calculated based on the reduction of this term from unconditional models containing only a constant and age terms.[14] In our final model, 98% of within person variance over time, 26% of between person variance in initial status and 14% in rate of change is explained by the predictors. Our final model also estimates a significant correlation of between person variation in initial status and rate of change indicating that children larger at birth also tend to have an elevated rate of growth.

Table 4 summarizes the final model for the effects of younger and older siblings. Note that initial status effects of younger sibling presence are estimated at 1 year, 9 months. This is the first point at which ALSPAC data codes their existence (Table 1).

Table 4 Final model: number of younger and older siblings and childhood height in millimetres

	Initial status		Rate of change	
Fixed effects	Coefficient	95% CI	Coefficient	95% CI
Intercept[a]	404.9	391.4–418.4	160.0	155.7–164.3
Additional age terms				
Age^2			−26.5	−26.3 to −26.8
Age^3			1.4	1.4–1.4
Number of younger siblings (Ref: 0)[b]				
1	−17.6	−19.5 to −15.7	1.1	0.6–1.6
2+	−15.8	−20.8 to −10.8	0.7	−0.1–1.5
Number of older siblings (Ref: 0)				
1	−2.5	−3.7 to −1.3	−1.1	−1.5 to −0.7
2+	−2.5	−4.1 to −0.9	−1.5	−2.0 to −1.0
Sex of child (Ref: Male)				
Female	−14.7	−15.8 to −13.6	0.8	0.5–1.1
Father presence (Ref: Presence)				
Mother Alone	−0.5	−4.3–3.3		
New Partner	−8.7	−11.0 to −6.4		
Mother's age at birth (Ref: <25)				
25–29	0.2	−0.3–0.7		
30–34	0.6	0.1–1.1		
35+	0.5	−0.2–1.2		
Mum's education (Ref: CSE/Voc)				
O-level	0.2	−1.3–1.7		
A-level	−0.7	−2.3–0.9		
Degree	−0.6	−2.4–1.2		
Income (Ref: <£200 per week)				
£200–299 per week			0.3	−0.1–0.7
£300–399 per week			0.5	0.0–1.0
£400+ per week			1.2	0.7–1.7
Home ownership (Ref: Rented)				
Mortgaged/buying	1.4	0.1–2.7		
Owned outright	−0.5	−2.3–3.3		
Financial difficulty score (Ref: Low)				
Medium			−0.2	−0.5–0.1
High			−0.6	−1.0 to −0.2
Ethnicity of child (Ref: White)				
Non-white			1.9	1.0–2.8
Mother's height in cm (continuous)	1.0	0.9–1.1	0.3	0.3–0.3

Variance components and pseudo R^2 statistics	**Coefficient**	**95% CIs**	**Pseudo R^2**
Within person			
σ^2e0	1066.6	1051.9–1081.3	0.98
In initial status			
σ^2u0	256.1	238.2–274.0	0.26
In rate of change			
σ^2u1	23.8	20.0–27.6	0.15
Covariance of σ^2u0 and σ^2u1	28.4	26.9–29.9	

[a]The estimated mean value for initial status and rate of change for the group with the baseline values for every factor included in the model.
[b]Initial status effects for this covariate are estimated at 1 year, 9 months.
Final N – 53 541.

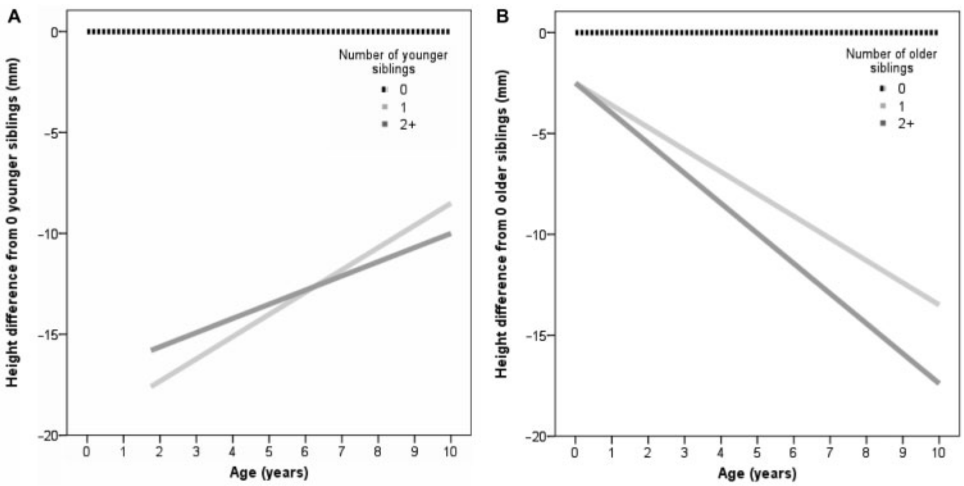

Figure 2 Sibling age configuration and estimated childhood height from birth to 10 years. (**A**) Height difference by number of younger siblings. (**B**) Height difference by number of older siblings

Compared with being the last-born child, having younger siblings was associated with early childhood deficits in height, evidenced by a reduced initial status effect (one younger sibling: −17.6 mm, CI: −19.5 to −15.7, $P < 0.001$; two or more younger siblings: −15.8 mm, CI: −20.8 to −10.8, $P < 0.001$). However, these deficits were recovered over time, represented by positive effects on rates of change per year (one younger sibling: 1.1 mm, CI: 0.6–1.6, $P < 0.001$; two or more younger siblings: 0.7 mm, CI: −0.1–1.5, $P = 0.080$). In contrast, compared to being a first-born child, having older siblings was associated with reduced initial status (one older sibling: −2.5 mm, CI: −3.7 to −1.3, $P < 0.001$; two or more older siblings: −2.5 mm, CI: −4.1 to −0.9, $P = 0.003$) and reduced rate of growth per year (one older sibling: −1.1 mm, CI: −1.5 to −0.7, $P < 0.001$; two or more older siblings: −1.5 mm, CI: −2.0 to −1.0, $P < 0.001$). At age 10 then, controlling for number of older siblings, we estimate last-born children as 7.8 mm taller than those with one younger sibling and 10.0 mm taller than those with two or more (Figure 2A). While controlling for number of younger siblings, we estimate first-born children as 13.5 mm taller than those with one older sibling and 17.4 mm taller than those with two or more (Figure 2B). Note unadjusted coefficient estimates are comparable to adjusted coefficients using the same sample for both younger sibling (initial status: one younger sibling: −17.6 mm, CI: −19.1 to −15.3, $P < 0.001$; two or more younger siblings: −16.6 mm, CI: −21.6 to −11.6, $P < 0.001$; rate of change: one younger sibling: 1.0 mm, CI: 0.5–1.5, $P < 0.001$; two or more younger siblings: 0.6 mm, CI: −0.2 to 0.8, $P < 0.156$) and older sibling effects (initial status: one older sibling: −2.6 mm, CI: −3.9 to −1.3, $P < 0.001$; two or more older siblings: −2.7 mm, CI: −4.5 to −1.0, $P < 0.001$; rate of change: one older sibling: −1.2 mm, CI: −1.6 to −0.8, $P < 0.001$; two or more older siblings: −1.8 mm, CI: −2.4 to −1.2, $P < 0.001$).

Table 5 summarizes the final model for the effects of brothers and sisters. The presence of both sibling sexes was associated with negative effects on initial status and rate of change of comparable magnitude. We also reran separate versions of this model for each sex and split by relative sibling age (results not shown). In all cases neither sibling sex was consistently more costly than the other. In both final models for sibling age (Table 4) and sibling sex (Table 5) the effects of other aspects of family configuration, parental resources, maternal height and model fit statistics show little deviation from the final sibship size model (Table 3).

Discussion

We demonstrate that, in the presence of a large range of time-varying covariates, the presence of siblings is associated with significant deficits in height over the first decade of life. Our results are consistent with prior cross-sectional based studies of growth to include family size as a covariate[15–17] and, all else being equal, suggests important negative health consequences of growing up in a large family, see also ref.[33] In developed countries, childhood height is strongly associated with adult height.[17] On average, taller adults have improved health status and live longer.[34,35] Lower levels of physical growth are also associated with reduced performance on cognitive measures and educational tests throughout life, probably because of shared nutritional and stress-related pathways.[36,37]

Table 5 Final model: number of brothers and sisters and childhood height in millimetres

Fixed effects	**Initial status** Coefficient	95% CI	**Rate of change** Coefficient	95% CI
Intercept[a]	404.3	390.4–418.2	160.1	155.6–164.6
Additional age terms				
Age^2			−26.4	−26.6 to −26.2
Age^3			1.4	1.4–1.4
Number of brothers (Ref: 0)				
1	−5.4	−6.6 to −4.2	−0.9	−1.3 to −0.5
2+	−4.1	−6.6 to −1.6	−1.2	−1.8 to −0.6
Number of sisters (Ref: 0)				
1	−5.2	−6.4 to −4.0	−0.7	−1.1 to −0.3
2+	−4.6	−7.2 to −2.0	−1.2	−1.8 to −0.6
Sex of child (Ref: Male)				
Female	−14.5	−15.6 to −13.4	0.9	0.6–1.2
Father presence (Ref: Presence)				
Mother Alone	−0.7	−3.1–1.7		
New Partner	−9.9	−13.9 to −5.9		
Mother's age at birth (Ref:<25)				
25–29	0.1	−0.4–0.6		
30–34	0.4	−0.1–0.9		
35+	0.2	−0.5–0.9		
Mum's education (Ref: CSE/Voc)				
O-level	−0.2	−0.3 to −0.1		
A-level	−1.5	−4.8–1.8		
Degree	−1.3	−3.1 to −0.5		
Income (Ref: <£200 per week)				
£200–299 per week			0.2	−0.3–0.7
£300–399 per week			0.5	0.0–1.0
£400+ per week			1.3	0.8–1.8
Home ownership (Ref: Rented)				
Mortgaged/buying	1.5	0.1–2.9		
Owned outright	1.2	−1.7–4.1		
Financial difficulty score (Ref: Low)				
Medium			−0.1	−0.4–0.2
High			−0.4	−0.9–0.1
Ethnicity of child (Ref: White)				
Non-white			2.2	1.2–3.2
Mother's height in cm (continuous)	1.0	0.9–1.1	0.3	0.3–0.3

Variance components and pseudo R^2 statistics	**Coefficient**	**95% CIs**	**Pseudo R^2**
Within person			
σ^2e0	1082.9	1067.3–1098.5	0.98
In initial status			
σ^2u0	251.7	233.2–270.2	0.27
In rate of change			
σ^2u1	23.2	19.2–27.4	0.17
Covariance of σ^2u0 and σ^2u1	28.2	26.7–29.7	

[a]The estimated mean value for initial status and rate of change for the group with the baseline values for every factor included in the model.
Final N – 49 153.

Given the unusually large number of independent measures of maternal socio-economic profile considered in our analysis, our results are unlikely to reflect confounding effects in this domain, which for example might be the case if low-socio-economic status mothers were more likely to have large families. Within family as opposed to between family resource variation offers a stronger candidate explanation, representing a trade-off in child number and individual allocations of parental resources. This explanation is consistent with studies of child health in developing country contexts[3,5] (where wealth and fertility are generally positively correlated) and experimental work in animal populations.[1,2] Furthermore, while the specific mechanisms of resource dilution are not identified by our analysis, effect magnitude decreases as sibling number increases consistent with a sibling competition model.[11]

To our knowledge, we are the first to demonstrate that sibling costs in relation to height are higher for later-born offspring. By age 10 the presence of older siblings was associated with height deficits of almost twice the magnitude of those estimated for the presence of younger siblings. Larger family size, particularly for later-born children, has been associated with lower uptake of childhood immunizations[38,39] and lower levels of health service consultation for childhood illness.[39,40] Such effects may reflect resource constraints on parents, who find it difficult to find time to attend to their children's healthcare. Recent analyses of dietary patterns at ages 4 and 7 years in ALSPAC have identified children with older siblings as significantly more likely to eat 'junk food' diets at both ages.[41] Younger siblings also had a negative effect, but only at age 7. High-parity mothers also suffer lower quality diets during pregnancy.[42] Thus, negative effects on health care quality and early life nutrition present strong candidate mechanisms. Relatively improved outcomes of low-birth order children has also been demonstrated on IQ[24,25] supporting a general higher cost to older relative to younger siblings. This birth order effect is absent when older siblings are deceased[25] strongly indicating post-natal resource dilution as the principal mechanism rather than pre-natal factors.

That height deficits associated with the presence of younger siblings appear largest in early life suggests that their negative effects are immediate to the high-energetic demands associated with pregnancy and young infant care for parents of newborn children. It may even be possible that younger siblings have negative effects on parental allocation of resources before their conception (e.g. if this period is associated with 'preparation costs' such as moving home or changes in parental relationships). However, to fully answer these questions requires comparison of individual growth trajectories in the preceding and subsequent periods to the arrival of a younger sibling. Unfortunately, lacking consistent data on the date of birth of younger siblings in our sample, we are unable to further investigate this issue.

Several lines of evidence suggest that pre- and post-natal parental investment may be biased towards sons in contemporary Western societies,[26–29] leading us to predict that male siblings would be more costly than female siblings. Consistent with this hypothesis, a recent Danish study has shown that children born after a brother relative to a sister have reduced birth weight.[43] However, considering childhood growth as a whole, we find no evidence that brothers are associated with larger height deficits than the presence of sisters. Education studies to examine the relative costs of brothers and sisters have also failed to support this model, demonstrating mixed results across similar study populations.[10] A simple model of 'costly sons' therefore seems to be an oversimplification.

Our analysis also indicates that the presence of non-related father-figures compared with biological fathers is associated with lower height for age across the study period, even after controlling for socio-economic factors which might covary with this aspect of family configuration. Similar findings have been documented on multiple outcomes elsewhere.[44–46] Such effects may be underpinned by a lack of genetic relatedness, associated with lower parental investment or even abuse,[46] although multiple pathways are likely.[44]

The major advantage of the multi-variate multi-level modelling strategy followed in this study is that it allowed us to incorporate all available outcome data in the cohort rather than restrict analysis to participants who provided complete height assessments at a specific subset of time points. Large sample analysis is particularly crucial to studies of sibling configuration in modern societies because modal fertility, and so variation in the independent variables of interest, is low. However, in order to have unbiased estimates in the presence of missing data, it must be assumed that responses are missing at random (MAR); that is, the probability of any child height measure being missing may depend on observed, but not unobserved, measures.[47] Although we do not formally investigate this issue, given the large range of relevant independent variables included in our models, it is likely that our analyses conform to the MAR assumption.

Apart from maternal height, measures of maternal physical condition are notably lacking from our analysis. However, it is likely that included socio-economic resource variables are sufficiently correlated with health variation in the cohort to account for a potential bias rendered by their exclusion. We also note that previous work on the ALSPAC cohort has established that maternal smoking is unrelated to parity,[48] so this factor is unlikely to represent residual confounding. One methodological factor which may have limited the accuracy of our models is the strategy we used to match time-varying independent variables with the height data over the study period. Assuming the value of each independent variable remained constant to the mid-point between each coding is clearly an imperfect reflection of reality. However, given the relatively small gaps in convergence between measures, and the relatively short total study period, we believe this serves as a reasonable approximation for the purpose of our study.

In conclusion, we have shown evidence that even in the relatively wealthy, well-nourished conditions of modern Western society, children are not buffered from the health costs of reduced parental investment. In addition to the effects we show on height, IQ and educational costs with related later outcomes on wealth accumulation are also likely.[10,11,24,25] Evolutionary life history models posit that such negative development outcomes will be further associated with lower Darwinian fitness.[1,2] Empirical tests of this claim using multigenerational data under the conditions of high-wealth inheritance that characterize modern populations are currently lacking. However, mathematical modelling by a number of authors suggest long-term fitness costs to siblings.[49,50] Researchers should look beyond simple models of sibling number to consider age and sex configuration. Most importantly, as evidenced here and elsewhere[24,25] later-born children appear the worst affected by within family resource division in contemporary Western populations.

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KEY MESSAGES

- Socio-economic differentials in health are well established phenomena. However, little research has directly considered health consequences of resource dilution within families.
- We demonstrate incremental negative effects of sibship size on height over the first decade of life consistent with a trade-off between number of children and parental resource allocations per child.
- By age 10, older siblings were associated with larger estimated height deficits than younger siblings. We find no evidence that sibling sex configuration is related to childhood growth.

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