You are what your mother eats: evidence for maternal preconception diet influencing foetal sex in humans

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Facultative adjustment of sex ratios by mothers occurs in some animals, and has been linked to resource availability. In mammals, the search for consistent patterns is complicated by variations in mating systems, social hierarchies and litter sizes. Humans have low fecundity, high maternal investment and a potentially high differential between the numbers of offspring produced by sons and daughters: these conditions should favour the evolution of facultative sex ratio variation. Yet little is known of natural mechanisms of sex allocation in humans. Here, using data from 740 British women who were unaware of their foetus's gender, we show that foetal sex is associated with maternal diet at conception. Fifty six per cent of women in the highest third of preconceptional energy intake bore boys, compared with 45% in the lowest third. Intakes during pregnancy were not associated with sex, suggesting that the foetus does not manipulate maternal diet. Our results support hypotheses predicting investment in costly male offspring when resources are plentiful. Dietary changes may therefore explain the falling proportion of male births in industrialized countries. The results are relevant to the current debate about the artificial selection of offspring sex in fertility treatment and commercial 'gender clinics'.

Keywords: sex ratio; nutrition; diet; mammal; fertility treatment; Trivers–Willard hypothesis

1. INTRODUCTION

The ability of parents to influence their offspring's sex should be favoured by natural selection (Trivers & Willard 1973; Myers 1978; Clutton-Brock 1991). Perhaps the best-known evolutionary theory of sex ratio variation, the Trivers and Willard hypothesis (1973), proposes that if increased parental condition differentially enhances the reproductive success of sons, then parents in good condition should favour male offspring. Competing hypotheses have also been proposed to explain differential sex ratio allocations in relation to resource availability and local conditions.

Whether such models can be expected to apply to modern-day humans might reasonably be disputed: not only do we have complex social structures that govern mating patterns but also resources are more readily available to us than to most wild mammals. Yet the technological age represents only a tiny fraction of the time scale over which reproductive strategies have evolved: phylogenetic inertia is therefore to be expected. In industrialized, as well as traditional societies, tall men and those of higher social status have greater reproductive success (Pawlowski *et al*. 2000; Fielder *et al*. 2005; Hopcroft 2006). Similarly, men exhibit more risk-taking behaviour than do women, particularly in young adulthood when sexual competitiveness is greatest (Daly & Wilson 1985; Wilson & Daly 1997; Kruger & Nesse 2007); men have strong preferences for physical traits associated with fertility (Buss *et al*. 1990); and they also have a much greater desire for multiple partners and short-term relationships than do women (Schmitt *et al*. 2001; Buss 2006). All of these traits are likely to have evolved because they contributed to reproductive success in an ancestral age. Human reproductive biology would be expected to favour the evolution of parental control over offspring sex, since there is low fecundity and high maternal investment, and sons are more costly to produce in both the short and long terms than daughters (Clutton-Brock & Iason 1986; Frank 1987; Hrdy 1999; Rickard *et al*. 2007; for further discussion of evolutionary context, see electronic supplementary material).

Weak relationships between sex ratios and the nutritional resources of mothers in late pregnancy and post-natally have been reported (Gibson & Mace 2003; Tamimi *et al*. 2003) but are controversial (Stein *et al*. 2003). Even if real, they do not imply any maternal command over foetal sex. Differential provisioning in late pregnancy or after delivery may reflect either manipulation of maternal metabolism and behaviour by the offspring, for example, through the action of foetal testosterone, or alterations in maternal behaviour due to knowledge of foetal sex (Shay 2003; Stein *et al*. 2003). The mechanism for controlling the sex ratio at birth in mammals is likely to be the differential conception and maintenance of male and female embryos (McMillen 1979). If there is maternal

manipulation of sex ratios in response to resource availability, then diet before and shortly after conception should be correlated with offspring sex: in non-human mammals, high resource availability around conception is consistently linked with male-biased sex ratios, whereas indices from later pregnancy or after birth produce contradictory results (Cameron 2004). We explored whether high resource availability around conception was linked with differential investment in male offspring in a large cohort of British women who were unaware of the sex of their foetuses. Determining whether infant sex is 'naturally' influenced by maternal conditions is of direct relevance to the current debate about the artificial selection of an embryo's sex during fertility treatment and in commercial 'gender clinics', and may offer insights into the falling proportion of male births in developed countries (James 2000; Davis *et al.* 2007).

2. MATERIAL AND METHODS

(a) *Study design and dietary assessment*

Nulliparous white women with no medical problems (including obesity) were recruited from a district general hospital in the south of England at their first antenatal clinic visit early in pregnancy (approx. 14 weeks gestation). Regardless of their medical history, all pregnant women in the region were referred to these clinics by their family physician; stratified random sampling was used to ensure that the proportion of smokers in the cohort represented that in the local population. Full details of the study methods have been reported elsewhere (Mathews *et al.* 1999). A total of 740 women with normal singleton pregnancies kept a prospective food diary of their diet in early pregnancy (hereafter referred to as 'early pregnancy' data); of these, 721 gave a retrospective report of their usual diet in the year prior to conception ('preconception' data) and 661 reported their usual diet during pregnancy at approximately 28 weeks gestation ('later pregnancy' data). Seventeen additional women provided dietary data, but were excluded from the analysis because they moved out of the district before giving birth. The women were 'blind' to the sex of their offspring at the time of completing their questionnaires: owing to hospital policy, offspring sex was not disclosed at ultrasound scans. The only mothers to know the sex of their infant during the study were those who had amniocentesis ($n=25$) or had abnormality scans ($n=27$): even here, the information was available only later in gestation, after the preconception and early pregnancy data had been obtained. All women provided written informed consent and the study was approved by the Research Ethics Committees of Portsmouth Hospitals and of the University of Oxford Medical School.

Food frequency questionnaires are the most widely used method of dietary assessment in epidemiological studies (including previous work on maternal provisioning; Tamimi *et al.* 2003), and substantial effort has been put into assessing their repeatability and validity (Willett 1990). The time scale for recall was relatively short (a matter of months) compared with many studies, for example, those evaluating risks of cancer or cardiovascular disease, which attempt to evaluate dietary exposures experienced years ago. Those adopted for this work have been used in large epidemiological studies in Europe are based on the questionnaire used in the US Nurses Health Study and have been validated (with comparable intervals between food consumption and recall) against a 7-day food diary (Bingham *et al.* 1997). Food diaries, as used in this project, are considered a 'gold standard' method of dietary assessment (Willett 1990). Further details of the methods used and their reliability are given in the electronic supplementary material.

(b) *Statistical analysis*

We explored the differences between proportions using χ^2-tests, and between means using Z-tests. Food and nutrient intakes were measured on interval scales and were always analysed as continuous variables. The groupings given in figures for illustrative purposes are derived from splitting as closely as possible to the tertiles; the unequal group size for breakfast cereals is due to the large numbers of women who habitually consumed cereal daily. Because intakes of different nutrients are correlated, we used principal components analysis (PCA; SAS FACTOR procedure) to summarize dietary patterns: the computed factor scores were used in further analyses. This method has been shown elsewhere to be a good method of summarizing dietary patterns, and is preferable to other methods such as cluster analysis, which result in the formation of categorical rather than continuous variables (Crozier *et al.* 2006). The joint effects of exposures were investigated using logistic regression (SAS GENMOD procedure). For the analyses of individual nutrient intakes and foetal sex, the ranks of intakes were used for data derived from the food frequency questionnaires. This was owing to the difficulties in assessing absolute intakes using this method and the technique reduces the leverage of outlying values. All tests of significance were two-tailed. Given the multiplicity of testing, we interpreted *p*-values conservatively for individual nutrient items.

In the simple multivariate models (SAS GLM type 1 models; used because the predictors were correlated), the coefficient for energy represents energy independent of the other nutrients in the model. For example, for a model including fat and energy, the term for energy represents energy from sources other than fat, i.e. carbohydrate, protein and alcohol. Alternatively, the residual method (Willett 1990) can be used to adjust specific nutrients for energy intakes. The relationships between the total energy intake and outcome and the nutrient density and outcome can then be analysed distinctly. Concordant results were obtained with our data whichever method of analysis was used.

3. RESULTS

Nutritional patterns were summarized separately for nutritional data from three time periods: usual intake before conception (preconception); intake at approximately 16 weeks gestation (early pregnancy); and usual intake between 16 and 28 weeks (later pregnancy). For each period, two derived factors encapsulated a high proportion of the variability in the data and can therefore be considered good summary statistics (table 1). The factor-loading patterns in all three time periods (correlations between the input variables and the scores) indicated that high scores for factor 1 described diets high in many nutrients including protein, fat, vitamin C, folate and a range of minerals; while high scores for factor 2, described diets high in the vitamin A components and vitamin B_{12} (table 1). The factor scores for the three time periods were correlated

Table 1. PCA factor loadings for daily dietary intakes, and proportion of variability in data encapsulated by the factors at each time point. (*Notes.* Because sodium is difficult to measure accurately with any dietary method due to variation between brands of processed food, and addition of table salt to food and cooking, it was not included in the PCA. Italics indicate PCA factor loadings with absolute values ≥ 0.70 which by convention indicate that the variables are excellent components of the factors (Comfrey & Lee 1992).)

	preconception		early pregnancy		later pregnancy	
	factor 1	factor 2	factor 1	factor 2	factor 1	factor 2
fat	*0.73*	0.25	*0.84*	0.07	*0.90*	0.11
protein	*0.88*	0.26	*0.74*	0.50	*0.79*	0.48
carbohydrate	0.60	−0.08	0.03	0.76	0.13	0.76
vitamin C	*0.85*	0.18	0.61	0.42	*0.81*	0.33
vitamin E	*0.70*	0.18	0.41	0.10	0.60	0.39
β-carotene	0.50	−0.13	0	0.59	0.10	0.67
retinol	0.01	*0.91*	0.67	−0.13	*0.83*	0.04
vitamin B_{12}	0.25	*0.82*	0.62	0.24	0.18	0.57
folate	*0.82*	0.11	0.36	*0.80*	0.47	*0.77*
iron	*0.84*	0.28	0.50	0.60	0.61	0.62
zinc	*0.86*	0.29	0.67	0.53	*0.79*	0.44
calcium	*0.74*	0.19	0.67	0.41	*0.81*	0.24
potassium	*0.89*	0.13	0.56	0.70	*0.71*	0.58
proportion of variability encapsulated by factor (%)	55.40	11.00	48.80	10.50	59.60	10.20

($r = 0.2$, $p < 0.001$), indicating some consistency in individual women's dietary intake over time.

Given the correlations between the dietary measures across time, we first tested whether dietary patterns overall were linked to offspring sex by using the factor scores from the different times as multivariate responses (MANOVA) and sex as a predictor. Factor 1 scores were influential (MANOVA $F_{3,620} = 2.6$, $p = 0.051$), but no models using factor 2 were significant. Further, a profile analysis, using the differences between the factor 1 scores in different time periods, indicated that the difference varied significantly across time (non-parallelism test: $F_{3,620} = 3.64$, $p = 0.03$). Inspection of the within-time period factor score pattern showed that the diet difference was greatest for the preconception diet, whereas there was not a significant difference for either early or later pregnancy (Wald $\chi^2 \leq 0.22$, $p \geq 0.47$). Factor 1 score was a significant predictor of foetal sex preconception (Wald $\chi^2 = 6.74$, $p = 0.00095$), with male offspring being more frequent among women with high scores. Factor 2 was not associated with foetal sex (Wald $\chi^2 = 0.22$, $p = 0.64$).

Having established the existence of relationships between preconceptional nutritional patterns and foetal sex, we went on to examine individual nutrients in more detail. As would be predicted from the factor pattern, factor 1 scores were highly correlated with energy intake ($r = 0.87$, $p < 0.001$): in logistic regression, energy intake gave a similar model fit to factor 1 (Wald $\chi^2 = 4.87$, $p = 0.023$). In support of the prediction that mothers with more resources before conception would have more sons, mothers of males had higher intakes of macronutrients and a range of micronutrients at this time than did mothers of females, when individual nutrients were used in the analyses (table 2). The proportions of male offspring born to women in different thirds of energy intake are illustrated in figure 1: the odds ratio for having a male infant was 1.5 for women in the highest third of energy intake compared with those in the lowest third (95% CI 1.1, 2.2).

The relationships between nutritional exposures and outcome variables may be analysed either in terms of absolute intakes, or in relation to total energy intake (intakes of many nutrients are positively correlated with total energy intake, and some, e.g. the macronutrients, are metabolized in proportion to total energy consumption; Willett 1990). After adjusting for energy in simple multivariate models, no other nutrient was independently associated with infant sex. Thus, an increased prevalence of male foetuses was associated with high maternal nutrient intakes, but not with high-nutrient density. Although the associations with energy are compatible with predictions from evolutionary approaches to sex ratio variation, it is possible that the causal mechanism involves other nutrients. In forward stepwise regression, potassium intake was selected as the predictor of offspring sex ($p = 0.004$) and no other variable was selected for inclusion in the model after adjusting for the effect of potassium.

No socio-demographic or anthropometric characteristic was a significant predictor of foetal sex (table 3). Nor was smoking status or caffeine intake prior to, or during, pregnancy (table 3). We also tested whether offspring sex was a nonlinear function of body mass index (BMI) to allow for the possibility that an optimum 'condition' exists on this continuum. There was no evidence for this (a quadratic function of BMI was not a significant predictor of offspring sex).

We then examined whether there is differential postconception investment in the foetus according to sex, possibly induced by the foetus itself. Nutrient intakes in early pregnancy, but beyond the period when most foetal losses occur—approximately 16 weeks gestation—were not associated with foetal sex (table 2). The same was true for later pregnancy (see electronic supplementary material). Thus, the additional energetic cost of producing a male infant, males being approximately 100 g heavier than females, does not appear to be met via detectable differences in maternal nutritional intake.

Table 2. Daily dietary intakes[a] by foetal sex.

| | preconception | | | | early pregnancy | | | |
| | median (lower, upper quartile) | | | | median (lower, upper quartile) | | | |
	male foetus ($n=360$)	female foetus ($n=361$)	χ^2	p-value	male foetus ($n=372$)	female foetus ($n=368$)	χ^2	p-value
energy (kcal)	2413 (1986, 2912)	2283 (1781, 2720)	4.80	0.029	2033 (1763, 2283)	2061 (1730, 2326)	1.06	0.304
total fat (g)	87.0 (70.7, 112.0)	85.5 (67.3, 106.2)	2.20	0.138	84.2 (69.6, 98.0)	84.8 (70.4, 101.3)	0.16	0.692
% energy from fat	33.5 (30.6, 37.0)	34.2 (31.0, 37.4)	0.59	0.441	37.6 (34.5, 40.7)	37.9 (34.7, 41.2)	1.43	0.232
protein (g)	95.9 (77.3, 113.9)	91.3 (73.7, 109.8)	7.25	0.007	71.7 (62.0, 84.2)	74.6 (61.8, 85.2)	0.68	0.409
% energy from protein	15.9 (14.3, 17.7)	15.7 (14.1, 17.6)	0.49	0.484	14.5 (12.9, 16.1)	14.6 (13.2, 16.0)	0.19	0.663
carbohydrate (g)	342 (281, 406)	323 (259, 384)	4.46	0.035	257.3 (220.5, 292.4)	255.2 (214.3, 293.1)	2.43	0.119
% energy from carbohydrate	52.8 (49.0, 56.1)	52.4 (49.0, 56.1)	0.08	0.784	47.4 (44.7, 50.5)	47.2 (43.6, 50.3)	1.51	0.219
vitamin C (mg)	111 (78, 72)	103 (72, 140)	2.29	0.130	76.5 (49.0, 109.8)	71.0 (46.0, 107.0)	0.72	0.397
vitamin E (mg)	8.0 (6.3, 10.4)	7.7 (6.0, 9.6)	2.75	0.097	8.0 (5.8, 11.3)	8.2 (6.0, 11.2)	0.03	0.872
β-carotene (μg)	1658 (998, 2564)	1479 (999, 2560)	0.00	0.975	897 (449, 1542)	869 (481, 1345)	0.83	0.360
retinol (μg)	469 (321, 888)	433 (302, 832)	0.14	0.708	406 (311, 503)	417 (317, 532)	0.62	0.432
vitamin B_{12} (μg)	7.2 (4.8, 10.9)	6.8 (4.5, 10.5)	0.02	0.875	3.7 (2.8, 4.7)	3.6 (2.8, 4.6)	0.02	0.879
folate (μg)	396 (321, 479)	367 (293, 460)	3.76	0.052	240 (189, 279)	236 (192, 292)	0.96	0.327
iron (mg)	14.6 (11.8, 18.3)	13.5 (11.1, 16.8)	4.14	0.042	10.2 (8.4, 12.2)	10.0 (8.7, 11.9)	1.04	0.308
zinc (mg)	12.0 (9.5, 14.9)	11.3 (9.1, 13.9)	4.45	0.035	8.0 (6.5, 9.5)	8.1 (6.7, 9.6)	0.02	0.880
sodium (mg)[b]	4267 (3445, 5105)	3944 (3226, 4807)	8.73	0.003	2976 (2534, 3553)	2971 (2522, 3547)	1.57	0.209
calcium (mg)	1246 (970, 1572)	1154 (905, 1437)	7.41	0.006	896 (725, 1103)	903 (721, 1129)	0.52	0.437
potassium (mg)	4630 (3952, 5492)	4342 (3646, 5190)	3.97	0.046	2952 (2516, 3390)	2967 (2462, 3478)	0.76	0.382

[a] Diet before conception was assessed using a food frequency questionnaire, and in early pregnancy using a 7-day food diary. The absolute values for intakes are therefore not directly comparable due to the methodological differences, but good agreement is obtained for the ranking of subjects (see electronic supplementary material).
[b] Sodium intake is difficult to measure accurately with any dietary method due to variation between brands of processed food and addition of table salt to food and cooking.
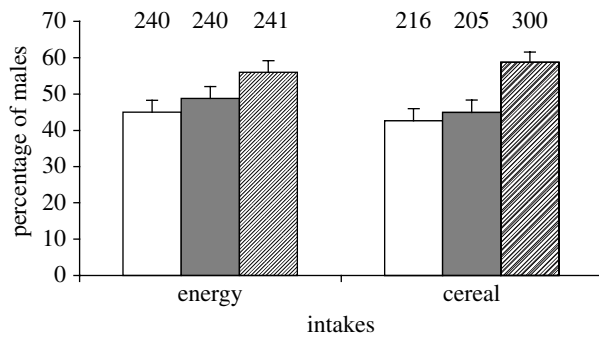
Figure 1. Relationship between usual maternal intakes of energy and breakfast cereal prior to pregnancy, split at approximate tertiles, and the proportion of male infants (+s.e.m.). Comparisons of the numbers of males and females across the groups were made using χ^2-test for linear association. The numbers above each bar indicate the numbers of women in each category of intake. For energy, the bars represent the low (open), moderate (filled) and high (hatched) thirds of intake; $\chi^2 = 5.83$, $p = 0.016$. For breakfast cereal, the bars represent less than one bowl per week (open), two to six bowls per week (filled) and one or more bowl per day (hatched); $\chi^2 = 13.96$, $p < 0.001$.

We went on to test whether particular foods were associated with infant sex. Data of the 133 food items from our food frequency questionnaire were analysed, and we also performed additional analyses using broader food groups. Prior to pregnancy, breakfast cereal, but no other item, was strongly associated with infant sex (Wald $\chi^2 = 8.2$, $p = 0.004$). Women producing male infants consumed more breakfast cereal than those with female infants (figure 1). The odds ratio for a male infant was 1.87 (95% CI 1.31, 2.65) for women who consumed at least one bowl of breakfast cereal daily compared with those who ate less than or equal to one bowlful per week. No other foods were significantly associated with infant sex (given the multiplicity of testing, $p \leq 0.01$ was considered significant), and was also true for the broader food categories. During later pregnancy, breakfast cereal consumption remained considerably higher among mothers of males (Wald $\chi^2 = 4.0$, $p = 0.04$). There were no differences for any other foods. Our data did not permit us to examine the consumption of breakfast *per se*, but breakfast cereal is the main food eaten for breakfast in the UK and is only rarely consumed at other times of day.

4. DISCUSSION

We have provided evidence of facultative selection of offspring sex by individual women according to environmental cues experienced around conception. The results fit into evolutionary frameworks developed with other species where, as in humans, males have greater potential lifetime reproductive success and are also more costly to produce (Trivers & Willard 1973; Myers 1978; Clutton-Brock 1991; see also electronic supplementary material). The overall sex ratio in our population was close to 50 : 50, but individual mothers had a greater chance of bearing male offspring if their nutrient intake was high prior to conception. The consumption of breakfast cereals was also strongly associated with having a male infant. The effect sizes in our study are striking even though our cohort was relatively well nourished. Parity is the main factor consistently associated with sex ratio in humans

(Novitski & Kimball 1958; Rostron & James 1977). The difference in sex ratio between women in the highest and lowest tertiles of energy intake is approximately 10 times more than that reported between women with first and third births, and is comparable with differences found in classic experimental manipulations of maternal nutrition in animals (e.g. Sachdeva *et al.* 1973; Labov *et al.* 1986).

The lack of dietary differences between mothers of sons and daughters during pregnancy itself is consistent with well-established observations that the very slow growth rate of the human foetus generates a lower incremental nutritional stress than in any other mammal: additional energy requirements, for example, are met via metabolic and behavioural energy-sparing mechanisms rather than increased intakes (Prentice *et al.* 1995). The marginally significant greater energy intake among pregnant mothers of males reported by one previous study (Tamimi *et al.* 2003) may have been due to maternal knowledge of foetal sex, or because preconceptional dietary patterns were carried over into pregnancy to a greater extent than in our cohort.

Although strong associations were seen for energy consumption, it is possible that any of the other correlated nutrients may be important in the aetiological pathway. There is tremendous interest in popular literature and the media about a possible link between dietary mineral intake (particularly calcium, sodium and potassium) and offspring sex (e.g. Chesterman-Phillips 2005). This is despite there being only scant support for the mechanism operating in humans (Papa *et al.* 1983) or animals (Cluzan *et al.* 1965; Bird & Contreras 1986). Doubt has also been cast on the mechanism of altered blood and vaginal pH linking offspring sex with mineral intake (Roche & Lee 2007). Although all of these nutrients did show highly significant associations with foetal sex in our study, we are cautious in the interpretation of the data until further research is available: the associations for sodium and potassium were in the predicted direction, but the association for calcium was not.

In general, the mechanisms of sex allocation in mammals are not well understood; however, a pathway has been proposed that could explain our associations of foetal sex with energy intake and breakfast cereal consumption around conception. *In vitro*, glucose enhances the growth and development of male conceptuses while inhibiting that of females (Larson *et al.* 2001). Skipping breakfast extends the normal period of nocturnal fasting, depresses circulating glucose levels and may be interpreted by the body as indicative of poor environmental conditions. A range of sequelae has previously been reported, including elevated risks of chronic diseases, such as non-insulin-dependent *Diabetes mellitus*, and abnormal blood glucose levels (Lecomte *et al.* 2002).

Various non-nutritional factors have been associated with sex allocation in humans, and these may act in concert with nutritional factors or may be confounded with them. These factors include environmental temperature (Helle *et al.* 2008); variations in hormonal profiles in women at around the time of conception according to their status and 'stress' levels (James 1990; Grant 2007); and the timing of insemination relative to ovulation (which is closely correlated with coital frequency since fertilization early in the cycle is more likely if there is frequent insemination; James 1971; Guerrero 1974; Harlap 1979).

Table 3. Maternal characteristics and foetal sex.

	% (n) or mean [s.d.]			
	male foetus ($n=372$)	female foetus ($n=368$)	test statistic[a]	p-value
current smoker[b]	39.0 (145)	42.4 (156)	0.89	0.35
cigarettes yesterday (n)				
0	73.9 (275)	69.8 (257)	1.72	0.27
1–8	14.8 (55)	17.4 (64)		
9–16	8.6 (32)	9.2 (34)		
17 or more	2.7 (10)	3.5 (13)		
folic acid used prior to conception	34.4 (128)	34.2 (126)	0.002	0.96
education				
<O level	23.1 (86)	19.6 (72)	1.40	0.50
O level	51.1 (190)	53.5 (197)		
>O level	25.8 (96)	26.9 (99)		
age (years)	25.8 [5.0]	25.8 [4.9]	0.01	0.92
weight prior to conception (kg)[c]	62.8 [11.7]	62.6 [15.0]	0.06	0.80
weight at booking (kg)[d]	67.2 [12.5]	66.2 [12.3]	1.16	0.28
height (cm)	164.3 [6.5]	164.3 [6.6]	0.01	0.91
body mass index prior to conception ($kg\,m^{-2}$)[c]	23.2 [4.0]	23.2 [5.3]	0.06	0.81
body mass index at first antenatal clinic ($kg\,m^{-2}$)[d]	24.9 [4.3]	24.5 [4.3]	1.18	0.28

[a] Wald χ^2-test for continuous and categorical predictors in logistic models.
[b] Defined by self-report or by a serum cotinine concentration greater than 14 ng ml^{-1} in self-reported 'non-smokers'.
[c] Data missing from medical records for 18 (4.8%) mothers of boys and 11 (3.0%) mothers of girls.
[d] Data missing from medical records for 9 (2.4%) mothers of boys and 11 (3.0%) mothers of girls.

Attention has focused particularly on the latter, with conceptions earlier in the oestrus cycle apparently being more likely to be male, and there being greater maintenance of male blastocysts if they are in synchrony with uterine ripeness (Krackow 1995). However, more recent clinical studies dispute these associations (Wilcox et al. 1995; Reubinoff & Schenker 1996). It remains to be seen whether women with greater nutritional intakes, and higher frequency of breakfast cereal consumption, prior to conception are also those with more active sex lives.

All methods of dietary assessment are prone to some degree of error. However, it is highly unlikely that these errors (formally, the within-subject differences between true and measured intakes) would produce spurious associations. Rather they will attenuate the observed associations between the outcome and exposure measures, depressing odds ratios towards zero: the generation of artefactual relationships would generally require differential misreporting of diet by women carrying male rather than female foetuses (Willett 1990; Clayton & Gill 1991; see electronic supplementary material). Given that the women in this study did not know the sex of their foetus, the latter possibility is unlikely.

Since all of the women in the study were white and nulliparous, we avoided the potentially confounding effects of race and birth order, both of which are associated with sex ratio (Novitski & Kimball 1958; Rostron & James 1977). Maternal age has not generally been associated with sex ratio independent of parity (Teitelbaum & Mantel 1971; Rostron & James 1977), and accordingly we found no association between any maternal age and sex ratio. Weight and condition measures are poor predictors of offspring sex in non-human mammals (Cameron 2004; Sheldon & West 2004), and we found no associations in our study. The measures are relatively weak indicators of resource availability, reflecting a combination of basal metabolic rate (a variable practically impossible to measure in large-scale studies), frame size and long-term levels of physical activity and dietary intake. Of these factors, variation in physical activity appears to be a major determinant of differences between individuals in energy expenditure, and is likely to explain why obesity is only poorly correlated with energy intake in epidemiological studies (Willett 1990). Although BMI (weight/height^2) is widely used as an index of body fat, it is error prone due to the large variation in lean body mass among people of the same height. Even in Ethiopia, a country with marked regional variations in the prevalence of maternal under-nutrition, the associations between such indices and infant sex are questionable (Shay 2003; Stein et al. 2003): from an evolutionary perspective, there is no reason to assume that body fat indices—reflecting historical imbalances between energy intake and expenditure—should be a good marker of resources currently available. For many nutrients, circulating levels are highly dependent on recent intakes and not on stored fat reserves. This is the case, for example, with water-soluble vitamins, and circulating glucose levels are influenced by the glycaemic index of foods. The recent finding that *change* in condition indices is more predictive of sex ratio than is condition *per se* (Roche et al. 2006; Cameron & Linklater 2007) further supports our contention that sex ratio is linked more directly to diet than to maternal condition.

Over the past 40 years, there have been small, but highly consistent, declines in the proportion of male infants born in industrialized countries (James 2000). This has caused considerable concern, and is regarded as a health sentinel, possibly of exposure to toxins (Davis et al. 1998; James 2000). However, population-level changes in the diets of young women may explain the pattern. Trends of declining mean energy intake over time among adults and children are reported by most (Heini & Weinsier

1997; Troiano *et al.* 2000; Fletcher *et al.* 2004) though not all (Nielsen *et al.* 2002) large-scale studies, with the current obesity epidemic being ascribed to declines in physical activity and alterations in the distribution of energy intakes. At the same time, there is good evidence that the prevalence of breakfast skipping is increasing, particularly among younger age groups: for example, in the USA, the proportion of adults consuming breakfast fell from 86 to 75% between 1965 and 1991, and for adolescent girls, the decline was from 85 to 65% (Haines *et al.* 1996; Siega-Riz *et al.* 1998). More work using biomarkers of nutrient status pre-pregnancy is warranted to further explore the relationship between infant sex and maternal resources.

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