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Heritability of Children's Dietary Intakes: A Population-Based Twin Study in China

Ji Li,[1] Huijuan Liu,[2] Terri H. Beaty,[3] Hua Chen,[2] Benjamin Caballero,[1] and Youfa Wang[1,3,4,5]

[1] *Department of International Health, Johns Hopkins University Bloomberg School of Public Health, Baltimore, MD, USA*
[2] *Jiaxing Maternity and Child Health Care Hospital, Jiaxing, China*
[3] *Department of Epidemiology, Johns Hopkins University Bloomberg School of Public Health, Baltimore, MD, USA*
[4] *Department of Health, Behavior and Society, Johns Hopkins University Bloomberg School of Public Health, Baltimore, MD, USA*
[5] *Systems-Oriented Global Childhood Obesity Intervention Program, Department of Epidemiology and Environmental Health, University at Buffalo, State University of New York, Buffalo, NY, USA*

Background: Despite evidence for some genetic control of dietary intake in adults, there is little evidence of how genetic factors influence children's dietary patterns. *Objective:* To estimate heritability of dietary intake in twin children from China and test if genetic effects on dietary intakes vary by the children's socioeconomic status (SES). *Methods:* A sample of 622 twins (162 monozygotic and 149 dizygotic pairs; 298 boys and 324 girls aged 7–15 years) was recruited in South China. Dietary intakes were assessed using a validated 145-item semi-quantitative food frequency questionnaire. Pooled and sex-specific dietary patterns were identified using factor analysis. Heritability was estimated using structural equation models. *Results:* Heritable components differed by gender and for nutrients and food groups; and estimated heritability of dietary patterns was generally greater in girls than boys. In boys, estimated heritabilities ranged from 18.8% (zinc) to 58.4% (fat) for nutrients; and for food group, 1.1% (Western fast foods) to 65.8% (soft drinks). In girls, these estimates ranged from 5.1% (total energy) to 38.7% (percentage of energy from fat) for nutrients, and 12.6% (eggs) to 94.6% (Western fast foods) for food groups. Factor analysis identified five food patterns: vegetables and fruits, fried and fast foods, beverages, snacks and meats. Maternal education and family income were positively associated with higher heritabilities for intake of meat, fried, and fast food. *Conclusions:* Genetic influence on dietary intakes differed by gender, nutrients, food groups, and dietary patterns among Chinese twins. Parental SES characteristics modified the estimated genetic influence.

■ **Keywords:** dietary intake, heritability, twins, children, China

Dietary intakes not only affect growth (Formica & Regelson, 1995; Silventoinen et al., 2009), body functions (Cameron et al., 2004), cognitive and behavioral development (Kar et al., 2008) in children, but also have long-term effects on health conditions in adulthood (Kemm, 1987; Moore et al., 2005). Childhood is a key time window for forming life-long eating behaviors. Without effective intervention, poor eating habits in early life could 'track' into adulthood and have long-term health consequences (Li & Wang, 2008; Wang et al., 2002; Zive et al., 2002).

Multiple factors influence children's dietary intake, which remain not well understood, in particular, regarding genetic influence. Family factors play an important role in affecting children's eating behaviors, which was partly reflected in the resemblance in diets between parents and their children (Beydoun & Wang, 2009; Kitzman-Ulrich et al., 2010; Wang et al., 2009). Observed parent–child correlations in dietary intakes may be due to shared genetics and environments. Population-based studies cannot distinguish genetic and environmental effects, whereas the twin study design can estimate the contribution of unobserved genetic factors to phenotypic variance of quantitative traits such as dietary intakes (Neale et al., 1992).

Twin studies have studied the heritabilities of dietary intakes among adults (Heitmann et al., 1999; Keskitalo et al., 2008; Teucher et al., 2007); however, such studies

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ADDRESS FOR CORRESPONDENCE: Youfa Wang MD, PhD, MS, Professor and Director, Systems-Oriented Global Childhood Obesity Intervention Program, Department of Epidemiology and Environmental Health, University at Buffalo, State University of New York, Kimball Tower, Buffalo, NY 14214-8001, USA. E-mail: youfawan@buffalo.edu

among children are scarce and have reported inconsistent findings. One study among twins aged 4–5 years in the United Kingdom showed that estimated heritability of food preference was 20% for dessert, 37% for vegetables, 51% for fruits, and 78% for meat and fish (Breen et al., 2006). Based on single 24-hour dietary recall data, a recent study of U.S. twins aged 7 years found apparent genetic effects varied by food groups and sex (Faith et al., 2008). The estimated heritabilities of consumption of a particular food group ranged from 12% (fish and lemon) to 79% (peanut butter and jelly) among boys, and from 20% (bread and butter) to 56% (fish and lemon) among girls. To our knowledge, no study has been conducted in developing countries, where the food choices are different from those in developed countries, and variation in dietary intakes and in people's dietary preferences may be larger (Darnton-Hill & Coyne, 1998; Khan & Bhutta, 2010). Additionally, the genetic composition of the population is different, which may lead to different findings.

This study aimed to quantify potential genetic influence on usual dietary intakes, including food patterns among Chinese children in a twin study. We also tested whether the genetic and environmental effects on children's dietary intakes might vary by family socio-economic status (SES). We hypothesized that SES such as maternal education and family income could affect food environments and parenting styles related to diet, and further influence the genetic effects on dietary intakes in children. We suspected better-educated mothers might assist their children to eat healthier, and thus these children might show a lower heritability of food consumption than their counterparts, whereas children in high-income families might have access to more abundant and various food groups, and thus might show a stronger heritability of food consumption than those from lower-income families.

Materials and Methods

Study Sample

We surveyed 622 twins aged 7–15 years old (n = 311 pairs, monozygotic (MZ) pairs: dizygotic (DZ) pairs≈1:1, male:female ≈1:1) and their mothers (n = 311) in December 2009–January 2010 in Jiaxing, Zhejiang Province, China. The twins were originally enrolled in the China Birth Defects and Child Health Care Surveillance System (BDSS-China), which has collected anthropometric data from each child since birth to age 7 (Li, Moore et al., 2003). Twins were recruited if (1) both twins participated in the BDSS-China, and (2) both twins and their mother consented or agreed to participate in the follow-up. Children with complete dietary data were included in the present study. Subjects ($n = 56$) were excluded mainly because their daily energy intakes were $<$450 kcal ($n = 2$) or $>$8,500 kcal ($n = 33$), or their co-twin did not have complete dietary data ($n = 21$). The final sample yielded 283 twin pairs (270 boys and 296 girls).

Data Collection

All twins visited one of the three clinics closest to their home on a designated weekend morning and completed the survey, which included blood draw. The mothers completed a questionnaire about demographic and family information. Children's anthropometry was measured by research physicians from the Jiaxing Maternity and Child Health Care Hospital (JMCHCH) following specific training for this study.

The study protocol was approved by the Institutional Review Boards of the Johns Hopkins University Bloomberg School of Public Health (JHBSPH) and JMCHCH, Jiaxing, China.

Dietary Assessment

Food consumption was assessed using a 145-item self-administered food frequency questionnaire (FFQ) that measured children's food intakes during the previous 12 months. In addition to 117 food items, the FFQ contained 28 questions on cooking methods, edible oil consumption, and so forth. The FFQ was initially designed for children in Beijing and validated against four 24-hour recalls, and showed good reliability and moderate validity (Wang, 2009). Subjects provided information on the amount and type of food consumed. Children were also provided with two-dimensional colorful pictures of measuring plates and bowls to facilitate estimation of portion size. Standardized interviews were conducted when necessary to help children better understand the questionnaire. All the interviewers were required to follow a standardized protocol for data collection.

Nutrients and Food Groups

Energy and nutrient intakes were calculated using the Nutrition Data Systems established by the Chinese Centers for Disease Control and Prevention (Yang, 2004; Yang et al., 2002). For micronutrients such as vitamin (Vit) A, Vit C, Vit E, calcium, zinc, and iron, nutrient density (μg/1000 kcal or mg/1000 kcal) was calculated by using 1,000X (absolute value of nutrient daily intake, μg or mg)/(daily calorie intake, kcal). High fat intake was defined as the age-specific top quartile of % energy (E) from fat. Based on similarity in nutrient content, the 117 food items were further categorized into 23 food groups (see Supplementary material). These food groups were used in our factor analysis to identify the dietary patterns.

Zygosity

MZ and DZ twins were ascertained by 19 questions in the mothers' questionnaire. The questions were adapted from a validated Taiwan twin similarity questionnaire (Chen et al., 1999) and based on other related research (Ooki & Asaka, 2004; Rietveld et al., 2000). The accuracy rate of the Taiwan questionnaire was 97.4% for parental reports and 95.6% for adolescent twins' self-reports compared to results based on

DNA diagnosis (Chen et al., 1999). Only one twin pair was asked to answer the questions because their mother did not answer them. Based on the participants' answers, we identified 146 MZ pairs, 73 same-sex (SS) DZ pairs, and 64 opposite-sex (OS) DZ pairs.

Other Measurements

Family information was collected from the parents. Mothers' education was grouped into two categories: (1) higher education (22 MZ and 11 same-sex DZ pairs) referred to senior high school or above, and (2) lower education (124 MZ and 62 same-sex DZ pairs) referred to junior high school, elementary school, or below. Annual family income was categorized into two groups: (1) higher income (42 MZ and 21 same-sex DZ pairs) meant income $\geq$50,000 Yuan ($\approx$7,457 USD) per year, and (2) lower income (102 MZ and 44 same-sex DZ pairs) an income $<$50,000 Yuan per year.

Statistical Analysis

First, to test if selection bias existed, we compared 566 eligible twins with 56 twins ($n = 28$ pairs) who were excluded due to incomplete FFQ data for one or both twins. The two groups did not differ significantly in their age, sex, zygosity, weight, height, BMI, maternal education, or family income status ($p > .05$). Second, we conducted descriptive analysis and analyzed the twin cohort as individuals; *t* tests, ANalysis Of VAriance (ANOVA), and χ^2 tests were conducted to compare differences between groups in continuous and categorical variables. Shrout–Fleiss intraclass correlation coefficients (ICCs) were calculated in boys and girls respectively using SAS 9.2 (SAS Institute, Cary, NC). ICC measures the degree of similarity in a quantitative trait between pairs of individuals. By comparing MZ and DZ ICCs, we estimated the genetic and environmental influences on each trait.

Third, factor analysis was conducted using SAS 9.2 (SAS Institute, Cary, NC) to identify dietary patterns for consumption of the 23 food groups separately among boys, girls, and in the pooled sample. Uncorrelated factors were derived using Varimax rotation. The number of factors was determined by considering the scree plots of eigenvalues (Supplementary material), as well as whether a factor had meaningful contents. Patterns were named based on the food items with the highest factor scores and the general nutritional content of foods that loaded highly on the pattern (Newby et al., 2006). A final five-factor solution was selected for each group.

Fourth, estimated heritabilities of intake of nutrients, food groups, and dietary patterns were computed for each gender using structural equation models (SEMs) with maximum likelihood estimation of the genetic and environmental component. Only MZ and same-sex DZ twins were included in the SEM analysis. If 1/2 rMZ was less than rDZ, ACE models were indicated as discussed below; if 1/2 rMZ was greater than rDZ, ADE models were indicated (Neale et al., 1992). We used energy adjustment in these models to control for recall bias, which adjusts for children's age when studying macronutrient and micronutrient density, and for age and daily calorie intake when studying food groups and dietary patterns. Genetic models were fitted using the OpenMx statistical package 0.3.3, which allows for variance component decomposition (http://openmx.psyc.virginia.edu). Submodels were compared. Model fit for SEM was assessed based on χ^2 tests. The best-fitting models were those with small χ^2 and high *p* value. A parsimonious model was identified by using Akaike's information criterion (AIC), and the model with the lowest AIC was preferred.

Total calorie intake was transformed to 100 times the natural log (ln) scale to correct its skewed distribution. The variance is partitioned into an additive genetic component (*a*), a non-additive genetic component (*d*), a shared non-genetic component (*c*), and a random component (*e*). MZ twins are genetically identical and DZ twins share on average 50% of their genetic background. Therefore, in MZ twins, $a_{i1} = a_{i2}$ and $d_{i1} = d_{i2}$ (where *i* means the *i*th twin pair; 1 and 2 means the birth order of this *i*th twin pair), $\text{cov}(a_i1, a_i2) = \sigma^2{}_a$ and $\text{cov}(d_{i1}, d_{i2}) = \sigma^2{}_d$ (cov means the covariance); in DZ twins, $\text{cov}(a_{i1}, a_{i2}) = \sigma^2{}_a/2$ and $\text{cov}(d_{i1}, d_{i2}) = \sigma^2{}_d/4$ (Falconer & Mackay, 1996). The heritability is then estimated as (estimated genetic variance)/(total variance) $\times$ 100%.

Finally, to assess whether genetic effects on dietary intakes varied by family SES, we fit univariate Cholesky decomposition models for food groups and dietary patterns stratified by maternal education and family income levels, respectively. The Cholesky decomposition is more frequently used in describing multivariate models. However, univariate Cholesky decomposition models have been used to examine genetic and environmental influences on various traits in previous twin studies as well (Hansell et al., 2015).

All genetic models were fitted using OpenMx for SEM, adjusting for child's age, sex, and daily calorie intake. Statistical significance of the regression coefficients was set at $p < .05$; $p < .10$ was set for marginal significance.

Results

Subject Characteristics

The mean ($\pm$*SD*) age was 11.7$\pm$2.6 years in boys ($n = 270$) and 11.6$\pm$2.4 years in girls ($n = 296$). OS DZ twins (11.3$\pm$2.5 years) were younger than MZ (11.8$\pm$2.5 years) and SS DZ (11.4$\pm$2.6 years) twins ($p < .05$). Table 1 shows the distribution of nutrient and food group intakes. Compared to girls, boys had higher intakes of zinc, refined grains, meats, eggs, soft drinks, snacks, and western fast foods, but lower intakes of Vit C and vegetables (all $p < .05$).

Intraclass correlation coefficients (ICCs) and heritabilities of energy and nutrient intakes. Twin-pair ICCs and

TABLE 1

Average Daily Dietary Intakes by Sex in Twin Pairs of Chinese Children Aged 7–15 Years (n = 566)[a, b]

	All (N = 566)		Boys (n = 270)		Girls (n = 296)	
	Mean	*SD*	Mean	*SD*	Mean	*SD*
Nutrients, unit/day						
Total energy (kcal)	2833.0	1587.7	2938.1	1659.0	2737.1	1516.1
Protein (g)	134.7	90.7	142.6	96.7	127.5	84.4[§]
Fat (g)	77.8	51.3	82.1	54.9	73.9	47.5[§]
Carbohydrate (g)	434.4	252.3	442.6	256.7	427.0	248.5
Protein, %*E*[c]	18.8	4.4	19.1	4.6	18.5	4.3
Fat, %*E*[c]	24.1	6.0	24.5	6.2	23.8	5.7
Carbohydrate, %*E*[c]	57.1	8.4	56.4	9.0	57.7	7.7[§]
Vitamin A (μg)	2009.9	1959.4	1973.9	1998.8	2042.8	1925.7
Vitamin C (mg)	294.6	282.8	261.8	246.1	324.5	310.0**
Vitamin E (mg)	35.9	26.5	34.8	25.3	36.9	27.6
Calcium (mg)	1252.6	909.2	1235.2	891.9	1268.4	925.8
Iron (mg)	41.7	30.1	43.4	32.1	40.2	28.1
Zinc (mg)	20.9	12.9	22.0	13.9	19.8	11.8*
Food groups, unit/day						
Grains						
Whole grain (g)	58.1	104.3	63.1	106.3	53.6	102.4
Refined grain (g)	534.8	300.9	577.4	345.2	496.0	248.2**
Meats, eggs, and fish						
Meats (g)	175.9	189.3	198.4	225.1	155.4	146.9**
Eggs (g)	37.4	59.5	44.5	74.0	30.9	41.2**
Fish and other seafood (g)	99.2	166.4	104.0	164.2	94.9	168.5
Dairy products (g)	172.3	208.5	180.0	183.4	165.3	229.1
Vegetables and fruits						
Dark green vegetables (g)	150.6	240.3	134.8	251.8	165.1	228.8
Beans and peas (g)	36.6	73.0	30.7	67.5	42.0	77.5[§]
Potatoes (g)	47.8	84.1	44.6	78.0	50.7	89.3
Other vegetables (g)	381.8	498.9	335.8	418.8	423.8	559.6*
Fruits (g)	692.6	845.1	630.4	794.9	749.3	885.9[§]
Tofu (g)	109.2	150.4	111.7	155.9	107.0	145.4
Nuts, snacks, and sweets						
Nuts (g)	14.6	27.8	12.9	26.4	16.2	28.9
Snacks (g)	3.3	5.3	3.8	6.0	2.9	4.6*
Chocolates (g)	11.8	36.0	11.9	41.7	11.8	30.0
Sweet desserts and candy (g)	110.0	137.4	110.4	156.0	109.6	118.2
Beverages						
Soft drinks (mL)	206.7	291.8	234.0	319.8	181.8	261.7*
Juices (mL)	54.5	119.0	56.5	132.7	52.7	105.1
Fried and fast foods						
Chinese fried foods (g)	7.0	29.8	9.8	40.2	4.4	14.5
Western fast foods (g)	9.2	27.8	10.4	29.3	8.1	26.4*

Note: [a]Based on FFQ. [b]Differences between groups were tested by *t*-tests. [c]Percentage of energy from the macronutrient. *Significantly different by sex, $p < .05$. **Significantly different by sex, $p < .01$. [§]Marginally significantly different by sex, $p < .1$.

heritability estimates suggested that genetic factors had important effects on nutrient intake among boys and girls. The results were shown by zygosity status and gender in Table 2. In boys, ICCs were greater for all nutrient measures except for percentage *E* from protein and zinc among MZ twins. For macronutrients, ICCs ranged from 0.26 (percentage E from protein) to 0.61 (total energy) for MZ twins and from 0 (percentage E from fat) to 0.68 (percentage *E* from protein) for DZ twins. For micronutrients, ICCs ranged from 0.38 (Vit A) to 0.55 (Vit E) for MZ twins, and from 0 (Vit E) to 0.52 (Zinc) for DZ twins.

Because rDZ was >1/2 rMZ for most dietary variables, ACE models were fitted. In the SEMs for heritability estimation, additive genetic components were detected for all dietary elements except percentage *E* from protein and Vit C after adjustment for age. Final estimates of heritability calculated under ACE models were moderate or strong.

In girls, ICCs were greater for 6 of the 13 variables among MZ twins compared to those in DZ twins. For macronutrients, the average and median correlations were 0.52 and 0.51 in MZ twins and 0.48 and 0.52 in DZ twins, respectively, suggesting that strong correlations not solely due to genes; for micronutrients, the average and median were 0.29 and 0.32 in MZ twins and 0.53 and 0.57 in DZ twins, respectively, again suggesting that genetics cannot explain much of the variation in these traits. Estimated heritability of nutrient intake ranged from 5.1% (total energy; A: 0.05, 95% CI: 0.00–0.58; C: 0.40, 95% CI: 0.00–0.58; E: 0.55, 95% CI: 0.40–0.71) to 38.7% (% *E* from fat; A: 0.39, 95% CI: 0.00–0.75; C: 0.27, 95% CI: 0.00–0.62; E: 0.34, 95% CI: 0.24–0.50). High fat intake was defined as the age-specific top quartile of %*E* from fat. Heritability of high fat intake in girls was 16.3% (A: 0.16, 95% CI: 0.00–0.91; C: 0.66, 95% CI: 0.00–0.91; E: 0.17, 95% CI: 0.05–0.41) greater than that es-

TABLE 2

Intraclass Correlation Coefficients (ICCs) and Heritability Estimates of Daily Nutrient and Food Group Intakes in Chinese MZ and DZ Twins[a,b]

	Boys			Girls		
	MZ (n = 144) ICC (95% CI)	Same-sex DZ (n = 62) ICC (95% CI)	h^2 (%) (95% CI)	MZ (n = 148) ICC (95% CI)	Same-sex DZ (n = 84) ICC (95% CI)	h^2 (%) (95% CI)
1. Macronutrients, unit/day						
Total energy (kcal)[c]	0.61 (0.46, 0.75)	0.52 (0.26, 0.78)	46.5 (0.0, 76.3)	0.47 (0.29, 0.65)	0.40 (0.15, 0.66)	5.1 (0.0, 58.0)
Protein (g)[c]	0.52 (0.35, 0.69)	0.50 (0.23, 0.76)	44.0 (0.0, 72.9)	0.51 (0.35, 0.68)	0.39 (0.13, 0.65)	14.7 (0.0, 62.0)
Fat (g)	0.61 (0.46, 0.75)	0.09 (0.00, 0.44)	58.4 (28.8, 71.6)	0.62 (0.47, 0.76)	0.54 (0.32, 0.75)	30.6 (0.0, 73.2)
Carbohydrate (g)	0.64 (0.51, 0.78)	0.59 0.35, 0.82)	24.2 (0.0, 73.1)	0.46 (0.28, 0.64)	0.56 (0.35, 0.77)	~
Protein, %E[d]	0.26 (0.05, 0.48)	0.68 (0.49, 0.87)	~	0.43 (0.25, 0.62)	0.37 (0.11, 0.63)	~
Fat, %E[d]	0.52 (0.35, 0.69)	0.00 (0.00, 0.35)	53.9 (27.0, 70.4)	0.61 (0.47, 0.75)	0.52 (0.30, 0.74)	38.7 (0.0, 75.1)
Carbohydrate, %E[d]	0.46 (0.28, 0.64)	0.18 (0.00, 0.53)	48.7 (5.6, 64.9)	0.55 (0.39, 0.71)	0.49 (0.26, 0.72)	15.9 (0.0, 65.6)
2. Micronutrients (nutrient density, per 1,000 kcal)						
Vitamin A (μg)	0.38 (0.18, 0.58)	0.04 (0.00, 0.39)	43.3 (7.8, 64.2)	0.37 (0.17, 0.56)	0.56 (0.35, 0.77)	~
Vitamin C (mg)	0.40 (0.21, 0.59)	0.39 (0.09, 0.69)	~	0.12 (0.00, 0.34)	0.58 (0.38, 0.78)	~
Vitamin E (mg)	0.55 (0.39, 0.71)	0.00 (0.00, 0.35)	53.2 (27.1, 68.7)	0.43 (0.24, 0.62)	0.26 (0.00, 0.54)	34.9 (0.0, 58.2)
Calcium (mg)[c]	0.50 (0.33, 0.68)	0.43 (0.13, 0.72)	25.8 (0.0, 67.4)	0.14 (0.00, 0.36)	0.71 (0.56, 0.86)	~
Iron (mg)	0.39 (0.19, 0.58)	0.21 (0.00, 0.55)	43.0 (0.0, 61.1)	0.27 (0.06, 0.48)	0.65 (0.47, 0.82)	~
Zinc (mg)	0.39 (0.19, 0.58)	0.52 (0.26, 0.78)	18.8 (0.0, 65.8)	0.38 (0.19, 0.58)	0.40 (0.14, 0.65)	~
3. Food groups, unit/day						
Grains						
Whole grain (g)	0.20 (0.00, 0.43)	0.55 (0.31, 0.80)	~	0.61 (0.47, 0.75)	0.14 (0.00, 0.44)	45.5 (0.0, 59.9)
Refined grain (g)	0.34 (0.14, 0.55)	0.53 (0.28, 0.79)	6.2 (0.0, 58.1)	0.48 (0.31, 0.66)	0.08 (0.00, 0.38)	38.2 (0.0, 54.5)
Meats, eggs, and fish						
Meats (g)	0.50 (0.33, 0.68)	0.19 (0.00, 0.53)	42.2 (1.8, 59.6)	0.55 (0.39, 0.71)	0.31 (0.03, 0.58)	62.2 (11.3, 74.4)
Eggs (g)	0.00 (0.00, 0.23)	0.03 (0.00, 0.38)	~	0.51 (0.34, 0.68)	0.36 (0.09, 0.62)	12.6 (0.0, 60.0)
Fish and other seafood (g)	0.16 (0.00, 0.39)	0.40 (0.10, 0.70)	~	0.19 (0.00, 0.41)	0.02 (0.00, 0.32)	~
Dairy products (g)	0.52 (0.35, 0.69)	0.12 (0.00, 0.47)	9.0 (0.0, 59.5)	0.20 (0.05, 0.42)	0.91 (0.86, 0.96)	~
Vegetables and fruits						
Vegetables and tofu (g)	0.36 (0.16, 0.56)	0.65 (0.44, 0.85)	~	0.29 (0.08, 0.50)	0.83 (0.74, 0.93)	~
Fruits (g)	0.26 (0.04, 0.47)	0.19 (0.00, 0.53)	9.8 (0.0, 43.2)	0.40 (0.21, 0.59)	0.08 (0.00, 0.38)	54.9 (10.5, 69.5)
Nuts, snacks, and sweets						
Sweet desserts, candy, chocolate, snacks, and nuts (g)	0.37 (0.17, 0.57)	0.07 (0.00, 0.43)	2.2 (0.0, 29.7)	0.42 (0.23, 0.61)	0.60 (0.40, 0.79)	~
Beverages						
Soft drinks (mL)	0.69 (0.57, 0.81)	0.10 (0.00, 0.45)	65.8 (44.5, 78.0)	0.17 (0.00, 0.39)	0.50 (0.27, 0.73)	~
Juices (mL)	0.50 (0.32, 0.67)	0.05 (0.00, 0.40)	~	0.25 (0.04, 0.46)	0.06 (0.00, 0.37)	82.1 (39.9, 90.0)
Fried and fast foods						
Chinese fried foods (g)	0.11 (0.00, 0.34)	0.03 (0.00, 0.39)	~	0.13 (0.00, 0.36)	0.00 (0.00, 0.31)	87.0 (74.8, 92.2)
Western fast foods (g)	0.18 (0.00, 0.41)	0.11 (0.00, 0.35)	1.1 (0.0, 33.5)	0.36 (0.16, 0.56)	0.17 (0.00, 0.46)	94.6 (88.2, 96.5)
Crude average for food groups	0.32	0.23	10.5	0.35	0.31	36.7

Note: ICC = intraclass correlation coefficients. [a]Shrout–Fleiss ICCs were calculated using SAS. [b]Heritability was estimated using ACE model: A, additive genetic effect; C, common environmental effect shared by a twin pair; E, residual environmental effect. The model was fit on each dietary phenotype using OpenMx. Macronutrients and micronutrients were adjusted for age; food groups were adjusted for age and daily calorie intake. ~ = heritability estimate was zero. [c]100 × log (the variable). [d]Percentage of energy from the macronutrient.

timated in boys (0.0%; A: 0.00, 95% CI: 0.00–0.72; C: 0.56, 95% CI: 0.00–0.79; E: 0.44, 95% CI: 0.21–0.76). Estimated additive genetic components were all non-significant for carbohydrate, %*E* from protein, Vit A, Vit C, calcium, zinc, and iron.

ICCs and heritabilities of food group intakes. Twin-pair ICCs and heritability estimates for each food group intake are shown by zygosity status and sex in Table 2. In MZ boys, ICC was lowest for eggs (0) and highest for soft drinks (0.69). In DZ boys, ICC was lowest for eggs and Chinese fried foods (0.03) and highest for vegetables and tofu (0.65). After adjustment for age and daily calorie intake, additive genetic components were statistically significant for 2 of 13 food groups (meats and soft drinks). The average heritability was 10.5%, which was low and non-significant.

Although the average ICC over all traits was 0.35 for MZ twins and 0.31 for DZ twins in girls, ICCs were greater for nine food groups among MZ twins than among DZ twins. Even after adjustment for covariates, the additive genetic components were still statistically significant for seven food groups. The average heritability was 36.7%, and the greatest heritability was for Western fast foods (94.6%; A: 0.95, 95% CI: 0.88–0.97; C: 0.00, 95% CI: 0.00–0.06; E: 0.05, 95% CI: 0.04–0.09), followed by Chinese fried foods (87.0%; A: 0.87, 95% CI: 0.75–0.92; C: 0.00, 95% CI: 0.00–0.05; E: 0.13, 95% CI: 0.08–0.25) and juices (82.1%; A: 0.82, 95% CI: 0.40–0.90; C: 0.03, 95% CI: 0.00–0.44; E: 0.15, 95% CI: 0.10–0.24).

Dietary patterns and their ICCs and heritabilities. Our factor analysis and five-factor solutions are presented in Table 3. The general and gender-specific patterns were similar and named according to their major contents. In girls, we excluded dairy foods from the factor analysis because of its low loading score (0.23). Factor analysis was then conducted among 22 food groups and also derived five factors.

Twin-pair correlation coefficients and heritability estimates for dietary patterns are shown by zygosity status and sex in Table 4. In terms of general patterns, ICCs ranged from 0.22 (snacks) to 0.65 (beverages) for MZ boys and from 0 (beverages and fried and fast foods) to 0.53 (vegetables and fruits) for DZ boys. Correlations were greater among MZ girls than among DZ girls for meats, and fried and fast foods. After adjustment for age and daily calorie intake, only heritability of fried and fast foods significantly differed between two sexes (based on 95% CI).

Regarding sex-specific patterns, in boys, ICCs ranged from 0.10 (snacks) to 0.68 (beverages) for MZ twins and from 0 (fried and fast foods and beverages) to 0.46 (vegetables and fruits) for DZ twins. In girls, ICCs were greater among MZ twins than among DZ twins for meats (0.57 vs. 0.06), beverages (0.42 vs. 0.20), and fried and fast foods (0.56 vs. 0.11).

After adjusting for age and daily calorie intake, estimated heritability was 35.2% (A: 0.35, 95% CI: 0.00–0.51; C: 0.00, 95% CI: 0.00–0.50; E: 0.65, 95% CI: 0.49–0.83) for fried and fast foods, 67.9% (A: 0.68, 95% CI: 0.46–0.81; C: 0.00, 95% CI: 0.00–0.10; E: 0.32, 95% CI: 0.19–0.54) for beverages, and 32.5% (A: 0.32, 95% CI: 0.00–0.51; C: 0.00, 95% CI: 0.00–0.37; E: 0.68, 95% CI: 0.49–0.89) for meats among boys, whereas in girls, it was 53.1% (A: 0.53, 95% CI: 0.22–0.71; C: 0.00, 95% CI: 0.00–0.16; E: 0.47, 95% CI: 0.29–0.73) for meats, 58.0% (A: 0.58, 95% CI: 0.02–0.71; C: 0.00, 95% CI: 0.00–0.49; E: 0.42, 95% CI: 0.29–0.59) for beverages, and 89.8% (A: 0.90, 95% CI: 0.82–0.94; C: 0.00, 95% CI: 0.00–0.07; E: 0.10, 95% CI: 0.06–0.18) for fried and fast foods. The additive genetic components were all non-significant for vegetables and snacks in both sexes. In addition, the variance components models showed common environmental components were statistically significant for vegetable dietary intakes and snacks in girls ($p < .01$) but not for any other food pattern in boys ($p > .05$), suggesting that common environmental effects were less important among boys.

Estimated heritability of children's dietary intakes by parental characteristics. Figure 1a and b shows heritability estimates of consumption of food groups and dietary patterns by maternal education and family income level, respectively. We did not present food groups or dietary patterns where the estimated heritability was zero in these two categories; that is, higher education versus lower education, richer versus poorer. Maternal education was positively associated with heritability for refined grain, meats, eggs, nuts, snacks, and Western fast foods, but negatively associated with that for fruits, soft drinks, and Chinese fast foods.

The twins from higher-income families had greater estimated heritabilities for most food groups (except for refined grains and Western fast foods). Consumption of meats, fried, and fast foods appeared to be more heritable, but less so for vegetables among children from richer families and among children with more educated mothers.

Discussion

To our knowledge, this study is the first to investigate the estimated genetic influence on usual dietary intakes among children in a developing country, China, and how the influence may vary by family characteristics. We found that estimated genetic effects were generally moderate, but varied by nutrients and food groups, and by maternal education and annual family income levels. ICCs were greater for 10 of 13 nutrient measures and 8 of 13 food groups in MZ boys than in DZ boys. In girls, MZ ICCs were greater for 6 of 13 nutrients and 9 food groups than DZ ICCs. Heritability of sex-specific dietary patterns ranged from 0% to 67.9% in boys and from 0% to 89.8% in girls. The apparent genetic component of intake of fried and fast foods was significantly greater among girls compared to boys. Overall, the results

TABLE 3

Dietary Patterns and Loading Scores of Food Items From Factor Analysis in Pooled Sample and by Sex[a]

Food groups	Pattern 1 Vegetables	Pattern 2 Meats	Pattern 3 Beverages	Pattern 4 Snacks	Pattern 5 Fried and fast foods
1. Boys and girls ($n = 566$)[b]	(16.2%)	(8.5%)	(6.6%)	(5.4%)	(6.3%)
Other vegetables	0.88				
Beans and peas	0.76				
Dark green vegetables	0.72				
Potatoes	0.70				
Tofu	0.37				
Fruits	0.31				
Red meat		0.64			
Poultry		0.60			
Fish and other seafood		0.56			
Processed meat		0.47			
Refined grain		0.47			
Whole grain		0.41			
Soft drinks			0.78		
Chocolates			0.77		
Juices			0.64		
Sweet desserts and candy				0.62	
Snacks				0.51	
Milk and yogurt				0.50	
Nuts				0.49	
Eggs				0.45	
Chinese fried foods					0.80
Western fast foods					0.74
Cheeses					0.56
2. Boys ($n = 270$)[c]	(15.8%)	(6.0%)	(7.5%)	(6.5%)	(8.9%)
Other vegetables	0.88				
Beans and peas	0.79				
Potatoes	0.64				
Dark green vegetables	0.60				
Tofu	0.50				
Fruits	0.37				
Red meat		0.64			
Poultry		0.56			
Refined grain		0.48			
Whole grain		0.48			
Fish and other seafood		0.45			
Processed meat		0.41			
Chocolates			0.84		
Soft drinks			0.78		
Juices			0.55		
Sweet desserts and candy				0.66	
Snacks				0.61	
Nuts				0.58	
Milk and yogurt				0.47	
Eggs				0.42	
Chinese fried foods					0.79
Western fast foods					0.78
Cheeses					0.63
3. Girls ($n = 296$)[d]	(18.5%)	(9.3%)	(7.2%)	(6.4%)	(5.5%)
Other vegetables	0.86				
Dark green vegetables	0.78				
Beans and peas	0.77				
Potatoes	0.74				
Fish and other seafood		0.66			
Poultry		0.63			
Red meat		0.61			
Processed meat		0.54			
Refined grain		0.49			
Tofu		0.39			
Juices			0.70		
Fruits			0.69		
Snacks			0.54		
Soft drinks			0.51		
Chocolates				0.65	
Eggs				0.43	
Sweet desserts and candy				0.39	
Nuts				0.36	
Whole grain				-0.32	
Chinese fried foods					0.75
Western fast foods					0.66
Cheeses					0.34

Note: [a]Loading scores were obtained from principle component analysis (PCA). The percentage of variance explained by each factor was presented in parenthesis. [b]Pooled patterns were obtained from the pooled sample (both boys and girls). A total of 23 food groups were included in factor analysis. [c]Boy-specific patterns were obtained from boys. A total of 23 food groups were included in factor analysis. [d]Girl-specific patterns were obtained from girls. Milk and yogurt was dropped due to their low loading (0.23). Then, a total of 22 food groups were included in factor analysis.

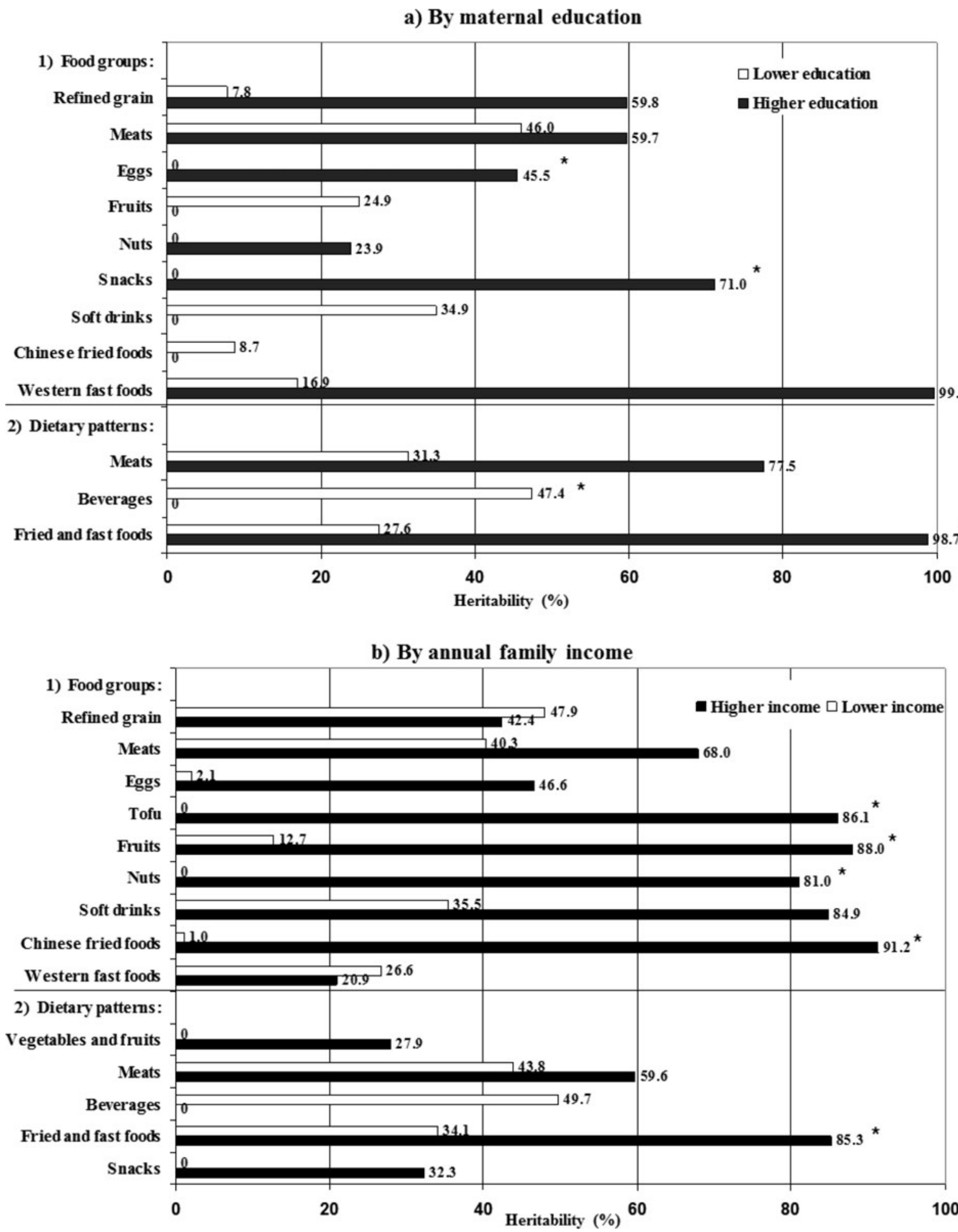

FIGURE 1

Estimated heritabilities of dietary intakes (food groups and dietary patterns) in Chinese child twins, by maternal education and family income. *Note:* Heritability was estimated using variance components models. The model was fit on each food group or dietary pattern and adjusted for age, sex and daily energy intake using OpenMx. Higher education: senior high school or above; lower education: junior high school, elementary school or below; higher income: income ≥50,000 Yuan (≈7,457 USD) per year; lower income: income <50,000 Yuan per year.

TABLE 4
Intraclass Correlation Coefficients and Heritability of Dietary Patterns by Sex[a,b]

Dietary patterns[c]	Boys MZ (n = 144) ICC (95% CI)	Boys Same-sex DZ (n = 62) ICC (95% CI)	Boys h^2 (%) (95% CI)	Girls MZ (n = 148) ICC	Girls Same-sex DZ (n = 84) ICC	Girls h^2 (%) (95% CI)
Based on factor analysis for pooled sample[d]						
Vegetables	0.31 (0.10, 0.52)	0.53 (0.27, 0.78)	~	0.41 (0.22, 0.60)	0.81 (0.71, 0.92)	~
Meats	0.27 (0.06, 0.49)	0.18 (0.00, 0.52)	28.1 (0.0, 47.1)	0.56 (0.41, 0.72)	0.10 (0.00, 0.40)	53.6 (21.6, 70.2)
Beverages	0.65 (0.52, 0.79)	0.00 (0.00, 0.35)	64.4 (39.9, 79.0)	0.35 (0.15, 0.55)	0.59 (0.40, 0.79)	~
Snacks	0.22 (0.00, 0.44)	0.02 (0.00, 0.37)	~	0.53 (0.36, 0.69)	0.60 (0.41, 0.80)	0.2 (0.0, 45.9)
Fried and fast foods	0.31 (0.10, 0.52)	0.00 (0.00, 0.35)	26.4 (0.0, 43.4)	0.53 (0.36, 0.69)	0.12 (0.00, 0.43)	92.9* (86.2, 95.5)
Based on sex-specific factor analysis[e]						
Vegetables	0.23 (0.01, 0.45)	0.46 (0.19, 0.74)	~	0.53 (0.36, 0.69)	0.81 (0.70, 0.91)	~
Meats	0.27 (0.05, 0.48)	0.14 (0.00, 0.49)	32.5 (0.0, 51.1)	0.57 (0.41, 0.72)	0.06 (0.00, 0.37)	53.1 (21.9, 71.1)
Beverages	0.68 (0.55, 0.80)	0.00 (0.00, 0.35)	67.9 (46.3, 80.6)	0.42 (0.23, 0.61)	0.20 (0.00, 0.49)	58.0 (1.87, 70.8)
Snacks	0.10 (0.00, 0.33)	0.29 (0.00, 0.61)	~	0.48 (0.31, 0.66)	0.78 (0.66, 0.90)	~
Fried and fast foods	0.41 (0.22, 0.60)	0.00 (0.00, 0.35)	35.2 (0.0, 51.0)	0.56 (0.40, 0.72)	0.11 (0.00, 0.41)	89.8* (81.8, 93.6)

Note: ICCs = intraclass correlations. [a]Shrout–Fleiss ICCs were calculated using SAS. [b]Heritability was estimated using ACE model: A, additive genetic effect; C, common environmental effect shared by a twin pair; E, residual environmental effect. The model was fit on each dietary phenotype using OpenMx and adjusted for age and daily calorie intake. ~ = heritability estimate was zero. [c]Food patterns were named the same for pooled and sex-specific analysis, but each food pattern may include different food groups (see Table 3). [d]Food patterns were obtained from the pooled sample (both boys and girls). [e]Sex-specific patterns were obtained from boys and girls, respectively. *Significantly different between boys and girls (based on 95% CI).

support our hypothesis that children in high-income families might have a stronger heritability of food consumption than those from lower-income families, but do not support our hypothesis for children whose mothers had more education.

Our study supports a genetic influence on usual dietary intakes in both boys and girls. We found some interesting sex differences in the estimated heritabilities. Sex-specific dietary patterns had greater point estimates of heritability than did the pooled patterns. Among boys, estimated heritability was higher for beverage consumption (67.9% vs. 58.0%), lower for meat consumption (32.5% vs. 53.1%), and lower for fried and fast foods (35.2% vs. 89.8%) than those of girls, whereas only heritability of 'fried and fast foods pattern' significantly differed between boys and girls. Girls had higher heritability of high fat intake than boys. This gender difference in estimated heritability of high fat food consumption may be related to human evolution, since energy and fat accumulation favors maturation and pregnancy (Dunger et al., 2006; Paul et al., 1979; Stoll, 1998). It may be also possible that social factors are prompting families with boys to feed them higher fat foods (Chunming, 2000) so that social factors override heritability for boys. Similar gender differences have been observed in previous research in children and adults (Faith et al., 2008).

In our study, although stronger genetic effects on nutrient intakes were found among boys than girls, who may be more susceptible to environmental factors, including influences from peers (Field et al., 1999; Field et al., 2001) and their parents or other care providers (Levine et al., 1994; Smolak et al., 1999), girls had higher heritability in more food groups. Such a discrepancy between nutrients and food groups could be due to the strong sex differences in usual dietary intakes among children. Note that although we named the sex-specific patterns using the same terms, each pattern included different food groups in boys and girls, and the boys' patterns were more similar to the pooled ones. For example, for boys, 'vegetables' included vegetables, tofu, and fruits, and 'meats' included meats, grains, and seafood; for girls, 'vegetables' solely included different types of vegetables, and 'meats' included meats, seafood, and tofu. Another reason may be gender difference in food sources of nutrients. In considering Vit A as an example, meats, eggs, and vegetables are Vit-A-rich foods. In our study, boys consumed significantly more meats and eggs, but less other vegetables than girls did. In addition, our results showed girls gave a higher estimated heritability for consumption of fried and fast food, but relatively weak estimates for total energy, fat and protein intake. This observation is not totally surprising since fried and fast foods are not the main food sources for total energy, fat and protein intakes among girls, which can be reflected by their daily consumption (4.4±14.5 g/day for Chinese fried foods, and 8.1±26.4 g/day for Western fast foods, Table 1). On the other hand, we found heritability of high fat intake (the top quartile of %*E* from fat) was greater among girls than boys.

Our SEMs suggested that shared environmental factors significantly influenced two dietary patterns among girls, but not among boys in our study. This result confirmed previous findings (Castro et al., 1993; Faith et al., 2008). No evidence of genetic influence was detected for consumption of several distinct food groups (including some vegetables, fish and other seafood) in our study. Previous studies have shown strong environmental influences on vegetable and fish consumptions. For example, at the family level, vegetable intakes were positively associated with education, household income, and availability of healthful foods in the home (Dehghan et al., 2011; Ding et al., 2012). At the community level, residential food retailers may also improve vegetable consumptions (Giskes et al., 2009; Rasmussen et al., 2006). Lower family food budget, income, and education levels may limit fish consumption (Jahns et al., 2014). An adult twin study reported similar findings as ours and showed strong shared environmental influence but not additive genetic influence on vegetable and fish intakes (Hasselbalch et al., 2008). It is noted that our findings could reflect true differences between these food groups and others (Faith et al., 2008), or it may be also due to the limitations of our FFQ assessment or the modest sample size.

Our data demonstrated that family SES factors modified the genetic influence on consumption of fried and fast foods, and beverages. Both higher maternal education and income magnified genetic effects on fried and fast foods, but lowered those on beverage consumption. The magnitude of changes in the heritable component of children's foods and dietary patterns across categories of maternal education and family income has not been examined in previous research. Maternal education was associated with food-related parenting practices (Saxton et al., 2009) and family income might affect household food environments (Larson et al., 2009). These family SES factors could potentially influence environmental variation in children's dietary intakes or diet-related genotypic expression, and further inflate the differences in estimated heritability. Our results supported our hypothesis about family income, but not regarding maternal education. It is possible that better-educated mothers do not necessarily have better nutritional knowledge, feeding, or parenting practices. For example, a study in urban areas of Beijing, China found that higher maternal education level was positively associated with inappropriate feeding practices ($OR = 2.44$, 95% CI: 1.42–4.19, $p < .05$; Li, Li et al., 2003). In addition, our sample size may not be large enough to detect an education effect.

This study has several main strengths. First, the twin study design allows separating influences of the genetic and environmental factors, and estimating their contributions to children's dietary intakes for different food groups (Neale et al., 1992). Second, compared with previous research (Breen et al., 2006; Faith et al., 2008), here, usual food intake was measured using a validated FFQ. The FFQ collected answers on the amount (weight or volume) and type of consumed foods. Third, we conducted comprehensive and vigorous analysis of dietary intakes—for example, nutrients, food groups, and dietary patterns. Heritability estimates were examined and stratified by sex and SES groups. Fourth, our study filled a major literature gap as no previous research has been done in developing countries to investigate heritability of dietary intakes.

Our study also has some limitations. First, although our FFQ was validated before use and showed good reliability with moderate validity (Wang, 2009), both boys and girls still tended to over-report their dietary intake. We tried to minimize the impact of over reporting by using nutrient density and energy-adjusted food groups and dietary patterns in our later analysis. Second, our sample may not have adequate statistical power to detect small genetic effects on dietary intake, although previous studies have used similar or smaller sample sizes (Breen et al., 2006; Faith et al., 2008; Hasselbalch et al., 2010). Third, although the food composition table used here reflects the most recent nutrient information, its food items are less than 3,000 and most of them are raw foods. The limitations of the food composition table may compromise our estimates of intakes of energy and nutrients, which may result in underestimation of heritability for nutrient intakes among our subjects. However, our main goal here was to examine the dietary patterns and rank the subjects based on their food consumptions. Thus, the weaknesses of the food composition table are not a major concern. Additionally, the food composition table and its earlier versions have been used for previous research, including some nationally representative studies (Ma et al., 2008; Popkin & Du, 2003; Popkin et al., 2002; Wang et al., 2002).

In conclusion, genetic factors affect usual dietary intakes in Chinese children, but the magnitude of the effects differed considerably by gender, nutrients, food groups, and dietary patterns. Genetic influence on dietary intakes can also be modified by family SES factors. This study sheds new light on genetic and environmental effects on children's dietary intakes in developing countries. Further longitudinal and genetic studies will be needed to fully understand the importance of genetic and environmental factors in children's eating behaviors, which is beneficial for early prevention of diet-related health risks.

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Supplementary Material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/thg.2016.61.

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APPENDIX

Food Included in Each of the 23 Food Groups That We Created for Our Dietary Pattern Analysis

Food groups	Food items included
Grains	
1. Whole grain	Whole wheat steamed bread, whole wheat bread, whole wheat clay oven rolls, corn buns, cereal congee, and breakfast cereals
2. Refined grain	Rice, noodles, rice noodles, wheat flour steamed bread, white bread, clay oven rolls, rice congee, dumplings, and wontons
Meats, eggs, and fish	
3. Red meat	Pork chops, pig feet, pig knuckles, pork (lean), pork (fat), lamb and mutton, and beef
4. Poultry	Chicken and duck meat
5. Processed meat	Canned meat, sausages, ham sausages, hams, preserved hams, preserved sausages, and bacon
6. Eggs	Fresh eggs, salty eggs, and preserved eggs
7. Fish and other seafood	Sea fish, river fish, shrimp, crab, sleeve fish, cuttlefish, seashell, mussel, and snail
Dairy products	
8. Milk and yogurt	Whole milk, low fat milk, whole milk powder, low fat milk powder, and yogurt
9. Cheeses	Cheeses
Vegetables and fruits	
10. Dark green vegetables	Spinach, bok choy, Chinese kale, mustard, brocolli, and dark green leafy lettuce
11. Beans and peas	Haricot beans, snake beans, cowpeas, horsebeans, string beans, kidney beans, green soy beans, and other fresh beans
12. Potatoes	Potato, yam, taro, and sweet potato
13. Other vegetables	All other vegetables including radish, carrot, garlic shoot, leek, onion, lotus root, mushroom, asparagus, sesame lettuce, pepper, Chinese watermelon, cucumber, vegetable marrow, towel gourd, balsam, bamboo shoot, tomato, eggplant, pumpkin, etc.
14. Fruits	Apples, pears, bananas, oranges, grapefruits, peaches, Kiwi fruit, apricots, plums, grapes, lichi, cherries, waxberries, longans, watermelon, cantaloup, pineapple, prunes, raisins, and other fruits
Tofu	
15. Tofu	Tofu, tofu pudding, tofu skin, vegetarian chicken, soybean milk, and bean curd
Nuts, snacks and sweets	
16. Nuts	Peanut, cashew, walnut, almond, chestnut, sesame, hazel, and melon seeds
17. Snacks	Potato chips, dried seaweed (salted), beef jerky, and meat floss
18. Chocolates	Chocolate bar, and chocolate powder
19. Sweet desserts and candy	Cookie, pie, puffed food, cakes, ice cream, and candy
Beverages	
20. Soft drinks	Sugar-sweetened soda, diet soda, dairy drinks, instant drinks, and tea drinks
21. Juices	Orange juice, apple juice, and grape juice
Fried and fast foods	
22. Chinese fried foods	Fried bread sticks, and spring rolls
23. Western fast foods	McDonald's, Kentucky Fried Chicken (KFC), hamburgers, pizza, and french fries