ORIGINAL CONTRIBUTION

Harnessing generalized structural equation modelling to understand the pathway linking maternal and child factors to fruit and vegetable intake trajectories from toddlerhood to adolescence

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Abstract

Purpose To identify longitudinal trajectories of fruit and vegetable intakes from toddlerhood to adolescence and examine integrative pathways with maternal and child factors in a multi-ethnic Asian cohort.

Method Data of 817 mother-child dyads from the GUSTO Study was used. Group-based trajectory modelling examined intake trajectories of fruits and vegetables from ages 18 months to 12 years. Generalized structural equation modelling evaluated the integrative direct and mediational pathways linking maternal and child factors to fruit and vegetable intake trajectories.

Results Two fruit intake trajectories: "High stable"(83.2%), "Low stable to decreasing"(16.8%) and three vegetable intake trajectories: "Consistently high"(78.8%), "Low to stable"(9.2%), "High decreasing"(12.0%) were identified. Malay ethnicity (vs. Indian) and boys (vs. girls) were directly and significantly associated with higher odds of adhering to the suboptimal "Low stable to decreasing" fruit intake (ORs 1.87 and 2.32) or "Low to stable/High decreasing" vegetable intake (ORs 3.49 and 1.80) trajectories, respectively. Every unit increase in maternal pregnancy diet quality score was significantly associated with 3–4% lower odds of following the suboptimal fruit or vegetable intake trajectory. Significant direct inverse associations were also observed between breastfeeding duration≥6 months (vs. <6 months) or maternal university education and lower odds of following the suboptimal fruit or vegetable intake trajectory. Pregnancy diet quality partially mediated the association between maternal ethnicity and suboptimal fruit or vegetable intake trajectory.

Conclusion Interventions to promote child fruit and vegetable intakes should begin preconception or during pregnancy, prioritise Malay mothers, those with lower education, families with boys, and improve maternal diet quality while promoting breastfeeding.

Keywords Fruit and vegetable intakes · Dietary trajectories · Longitudinal modelling · Maternal and child factors · Maternal ethnicity

Abbreviations

DOHaD	Developmental origins of health and disease
FFQs	Food frequency questionnaires
GBTM	Group based trajectory modelling
GSEM	Generalized structural equation modelling
GUSTO	Growing up in Singapore towards healthy outcomes
HEI-SGP	Healthy eating index for pregnant women in Singapore
WHO	World health organization

Introduction

As rich sources of essential vitamins, minerals, dietary fibre, and antioxidants, fruits and vegetables are essential components of a healthy diet to maintain good health and well-being. Low fruit and vegetable intakes have been associated

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with an elevated risk of chronic diseases such as obesity, heart disease and certain cancers [1, 2]. Estimates from the World Health Organization (WHO) in 2017 showed that 3.9 million deaths globally were attributable to low fruit and vegetable intakes [3]. Despite the emphasis on increasing fruit and vegetable intake, low fruit and vegetable intake remains a global concern, affecting many countries worldwide [4–6].

Compelling evidence has shown food preferences and dietary habits are established early in life and are hard to change once established [7], highlighting early life as a critical window for initiation of dietary interventions. The developmental origins of health and disease (DOHaD) concept also cements the importance of early life exposures in programming later health behaviours [8, 9]. Several maternal and child factors such as maternal ethnicity, education, and dietary intakes and child sex were shown to be associated with fruit and vegetable intakes in children and adolescents [10]. However, existing evidence largely stems from cross-sectional associations with a paucity of research on factors influencing longitudinal trajectories of fruit and vegetable intakes [10].

Investigating determinants of dietary trajectories can uncover key factors influencing dietary changes over time, identify the critical time points when relationships start to emerge, and characterize at risk populations with suboptimal dietary trajectories. Such insights will inform when and with whom to initiate dietary interventions. Additionally, emerging studies primarily assessed trajectories of dietary quality or patterns and their influencing factors with very few investigating trajectories of food group intakes [11]. Studying changes in different components of diet (i.e., food groups) is fundamental to inform tailored interventions and guidelines specific to food groups such as fruit and vegetables [11].

Current literature typically uses multivariable regression to examine the independent associations of prenatal or postnatal factors with fruit and vegetable intakes, without considering the interplay between factors [9]. In this study, we utilize generalized structural equation modelling (GSEM) to delineate the respective sequential pathways linking maternal and child factors and fruit and vegetable intake trajectories. Unlike traditional regression, GSEM allows us to simultaneously model integrative pathways, including mediation, providing insights into how maternal and child factors jointly influence these trajectories and their relative contributions. In an Asian multi-ethnic cohort, the current study aimed to (1) describe intake trajectories of fruits and vegetables from toddlerhood to adolescence and (2) apply GSEM to identify maternal and child determinants of fruit and vegetable intake trajectories and quantify their relative contributions via direct and indirect pathways.

Methods

Study design and participants

Data from the Growing Up in Singapore Towards healthy Outcomes (GUSTO) cohort was used. The GUSTO cohort study is an on-going mother-offspring cohort aimed at evaluating the roles of pregnancy and early life factors including genetics, environmental and lifestyle factors in influencing child growth and development, and long-term programming of health and disease [12]. At study baseline, 1450 pregnant women aged 18 years and over who were Singapore citizens or permanent residents of Chinese, Malay or Indian ethnicity were recruited at their first trimester antenatal appointment from two major public maternity units in Singapore (National University Hospital and KK Women's and Children's Hospital) between June 2009 and September 2010. Informed written consent was obtained from each participant. Ethical approval was obtained from the Sing-Health Centralized Institutional Review Board and National Healthcare Group Domain Specific Review Board (CIRB 2018/2767/D; DSRB D/2009/00021 and B/2014/00406). The detailed study protocol has been published [12]. The current analyses used data from mother-child dyads who participated in follow-up assessments at ages 18 months, 5, 7 and 12 years.

Assessment of fruits and vegetable intakes

Child dietary intake was assessed at ages 18 months, 5, 7 and 12 years using quantitative food frequency questionnaires (FFQs). Development and validation of the FFQs have been reported elsewhere [13–15]. FFQs were completed by mothers from ages 18 months to 7 years, and by children at age 12 years. The FFQs captured frequency of food intake in the past month. Notably, the FFQ items were age-specific, with more food items being administered at ages 5 and 7 years than age 18 months. However, an abbreviated FFQ was administered at age 12 years to ease child participant burden. This variation limits direct comparability of absolute intake levels across ages but allows identification of relative trajectory patterns. Mothers or children reported the portion sizes of each food item using household measurements or standard cups, spoons and plates used in the Singapore setting. Frequency of intake per month was converted into daily equivalents. Intakes of each food item (grams per day) were obtained as daily equivalents multiplied by portion size reported by mothers or children [16]. For the current analysis, fruit intake was calculated as the daily intake of all fresh and dried fruit items. Vegetable intake was calculated as daily intakes of all vegetable items,

excluding potato. Detailed fruit and vegetable items being captured over four time points are presented in Supplementary Table 1.

Assessment of maternal and child factors

At 26–28 weeks gestation (third pregnancy visit), maternal age (in years), smoking status (current smoker/past smoker vs. non-smoker), ethnicity (Chinese vs. Malay vs. Indian), education (secondary and lower vs. post-secondary vs. university) and household income (Singapore dollars) were ascertained using questionnaires. Maternal height was measured to the nearest 0.1 cm using a Seca 213 Portable Stadiometer (SECA, Hamburg, Germany). Weight was measured to the nearest 0.1 kg using a calibrated electronic weighing scale (SECA 803: SECA, Hamburg, Germany). Measurements were performed in duplicates and the average of readings were used. Maternal dietary intake during pregnancy was assessed using a 24-hour recall administered by trained staff [17]. Overall diet quality was assessed using the Healthy Eating Index for pregnant women in Singapore (HEI-SGP) [18]. HEI-SGP has a score range of 0 to 100 that evaluates adequacy and quality of food groups and adherence to antenatal supplement recommendations with higher score indicating a better diet quality. Breastfeeding duration (≥ 6 versus < 6 months) was estimated using infant feeding questionnaires administered when infants were 3, 6, 9, and 12 months of age, where breastfeeding was defined as any consumption of breastmilk regardless of what else was consumed by the infants [19].

Statistical analysis

Group based trajectory modelling (GBTM) [20, 21] was conducted to identify distinct trajectories of fruit and vegetable intakes (grams/day, log-transformed) at ages 18 months, 5, 7 and 12 years. GBTM identifies heterogenous groups within the sample that follow distinct trajectories [20, 21]. Censored normal distribution was assumed specifying linear, quadratic, and cubic functions of child age in months as independent variables and repeated measurements of fruit or vegetable intakes as the outcome variable. The polynomic function of age allows a non-linear trajectory in each group. Models with two to five groups were conducted. Fruit and vegetable intakes were log-transformed before GBTM analyses to account for non-normal distribution and varying number of fruit and vegetable FFQ items being used to capture intakes at various time points. Selection of final number of trajectory groups was based on several criteria: Bayesian Information Criteria (BIC), model parsimony (simpler models), proportion of individuals in each group

($> 5\%$), entropy (a measure of classification accuracy, range 0–1, higher values indicate better separation), and interpretability. Larger BIC (less negative) and entropy indicate a better model fit [20, 21].

Descriptive analysis was conducted to summarize sample characteristics by identified fruit and vegetable intake trajectory groups. Associations between maternal and child factors and identified fruit and vegetable intake trajectories were examined using generalized structural equation modelling (GSEM) [22]. GSEM examines direct associations between various factors and the outcome of interest by estimating multiple pathways simultaneously and allows estimation of total and indirect (mediational) pathways. By comparing the strength of the path coefficients between factors and outcome of interest, relative contributions of factors can be determined. Separate GSEM with a maximum likelihood estimation was conducted for fruit and vegetable intake trajectory groups, respectively. Continuous variables (maternal pregnancy BMI, maternal pregnancy diet quality, child birth weight) were analysed using Gaussian family with identity link, whereas categorical variables (maternal ethnicity, education, smoking, breastfeeding duration, child sex, fruit/vegetable trajectory groups) were analysed using binomial family with logit link. For ease of interpretation, maternal ethnicity was coded into two dummy variables representing 'Malay' versus 'Chinese' and 'Indian' versus 'Chinese'. Likewise, maternal education was coded into 'university education' versus 'secondary education or lower' and 'post-secondary education' versus 'secondary education or lower'. Household income was not examined as a determinant as it was highly correlated with maternal education ($r = 0.60$) and had higher missingness than maternal education (8% vs. 3%).

Various GSEMs were constructed by including all possible pathways (or associations) based on theoretical plausibility and prior literature. Model selection was based on comparison of model fit statistics (i.e., likelihood ratio test, and Akaike and Bayesian information criteria) and clinical interpretability. Maternal age and child birth weight showed no significant association with fruit and vegetable intake trajectories and removal of both improved the model fit (Likelihood ratio test: $\chi^2(11) = 173.40$, $P < 0.001$ for fruit; $\chi^2(11) = 174.58$, $P < 0.001$ for vegetable). Hence child birth weight was excluded in the final GSEM model. The best fitting model included the following pathways (exposure ⟶outcome):

- Child sex, maternal ethnicity, maternal education, maternal pregnancy diet quality, pregnancy BMI, pregnancy smoking status, breastfeeding duration ⟶ Low fruit or vegetable intake trajectory group.
- Maternal ethnicity ⟶ Maternal education.

- Maternal ethnicity, maternal education ⟶ Maternal pregnancy BMI.
- Maternal ethnicity, maternal education, maternal pregnancy smoking ⟶ Maternal pregnancy diet quality.
- Maternal ethnicity, maternal education ⟶ Maternal pregnancy smoking.
- Maternal education, maternal pregnancy BMI, maternal diet quality, maternal pregnancy smoking ⟶ Breastfeeding duration.

The "program" command was used to conduct nonparametric bootstrapping of 1000 replicates to obtain bias-corrected and normal-based confidence intervals for all pathways. The indirect (mediational) effect was obtained by the product method (calculated as the product of exposure-mediator *(a)* and mediator-outcome *(b)* path coefficients) and total effect was calculated as the sum of direct and indirect effect [23]. Percentage mediation was estimated as indirect effect divided by total effect. All analyses were conducted in Stata 18 (StataCorpLLC) with statistical significance set at $P < 0.05$ (two-sided).

Results

Children with two or more dietary intake measurements over four time points were included in the analyses to identify fruits and vegetable intake trajectories ($n=817$). Children with missing data on child and maternal factors ($n=136$) were excluded, resulting in 681 children being included in the GSEM analysis (Supplementary Fig. 1). Comparison of sample characteristics between those included and excluded from the analysis showed that excluded participants had lower birth weight (mean difference: -0.17 kg, $p<0.001$), younger mothers (mean difference: -1.29 years, $p<0.001$),

lower maternal pregnancy diet quality (mean difference: -2.04 scores, $p=0.015$), lower proportion of mothers with Indian ethnicity (15.6% vs. 21.7%, $p=0.008$) and university education (30.4% vs. 35.1%, $p=0.023$). However, child sex, maternal pregnancy BMI, pregnancy smoking status and breastfeeding duration did not differ between those included and excluded from the current analyses (Supplementary Table 2).

Fruit and vegetable intake trajectories

For fruit intake, relative to the model with 2 groups, models with 3–5 groups showed better BIC and entropy, but one of the groups had <5% of the sample. Thus, the model with 2 groups (BIC: -4500.4, entropy: 0.89) with good interpretability was chosen for fruit intake. For vegetable intake, the model with 3 groups was selected as it had relatively good BIC (-4878.6), entropy (0.88), and interpretability compared to other models with 2, 4 and 5 groups (Supplementary Table 3).

Fruit and vegetable intake trajectory groups from ages 18 months to 12 years are illustrated in Fig. 1. For fruit intake trajectories, most children (83.2%) followed a "High stable" intake trajectory with fairly stable intakes from age 18 months to 12 years. The remaining children (16.8%) had stable intakes from ages 18 months to age 7 years followed by a sharp decline until age 12 years. As it had lower intakes of fruit over time than the other group, it was named as the 'Low stable to decreasing' fruit intake trajectory group (Fig. 1).

Two of the three vegetable intake trajectory groups had high baseline intakes at age 18 months. Of these, one group (78.8%) exhibited consistently high intakes across all time points, with a slight dip from ages 5 to 7 years, and then an increase until age 12 years. In contrast, the other group
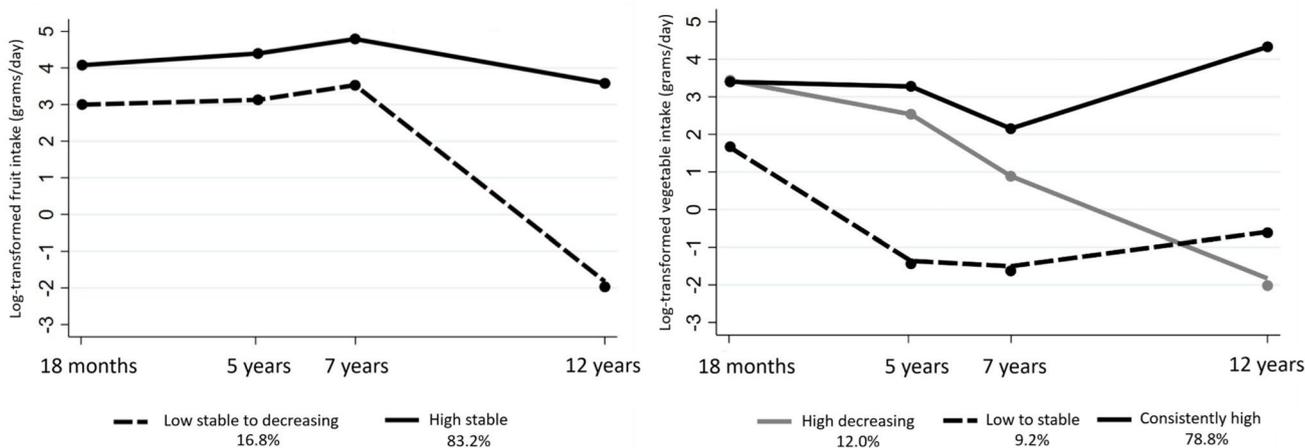

Fig. 1 Fruit and vegetable intake (log-transformed) trajectories from ages 18 months to 12 years the GUSTO cohort

(12.0%) started with high baseline intakes but continued with a sharp decline in intake subsequently, until age 12 years. The two groups are named as the "Consistently high" and "High decreasing" vegetable intake groups, respectively. The third group (9.2% of children) showed low baseline intakes, followed by a decline until age 5 years, but intake stabilized until age 12 years and is referred as the "Low to stable" vegetable intake trajectory group (Fig. 1).

Sample characteristics by identified fruit and vegetable intake trajectory groups

Comparison of sample characteristics by fruit intake trajectory groups is shown in Table 1. Compared to the 'High stable' fruit intake trajectory, the 'Low stable to decreasing' fruit intake trajectory group had a lower proportion of girls and children who were breastfed for more than 6 months. Moreover, the 'Low stable to decreasing' fruit intake group had a higher proportion of mothers who were smokers, of Malay ethnicity, below university education, lower diet quality during pregnancy, but higher pregnancy BMI than the 'High stable' group (all $P<0.05$). No evidence of significant differences was found in birth weight or maternal age according to the two fruit intake trajectory groups.

Results for the vegetable intake trajectory groups were largely similar for most factors apart from maternal age and ethnicity. Relative to the 'Consistently high' vegetable intake trajectory group, the 'High decreasing' and 'Low to stable' groups had a lower proportion of girls, children whose mothers were non-smokers and had university education. Mothers of children from the 'High decreasing' and 'Low to stable' groups also had higher BMI but lower diet quality during pregnancy than the 'Consistently high' group ($P<0.05$). 'Low to stable' group had mothers who were slightly younger than the 'High decreasing' and 'Consistently high' groups ($P<0.05$). For maternal ethnicity, the 'Low to stable' group and the 'Consistently high' group had about two third of children whose mothers were of Malay or Chinese ethnicity, respectively. In contrast, the 'High decreasing' group had a similar proportion of children with mothers of Chinese and Malay ethnicity. No between-group differences were found for birth weight (Table 1).

Direct and indirect pathways linking maternal and child factors and suboptimal fruit intake trajectory

Figure 2 illustrates direct associations between maternal and child factors and the 'Low stable to decreasing' versus 'High stable' fruit intake trajectory groups. Due to lower overall intake or declining patterns, 'Low stable to decreasing' is referred as the 'suboptimal' fruit intake group thereafter for simplicity and ease of interpretation. Child sex, maternal ethnicity, pregnancy diet quality score, and breastfeeding duration were directly associated with a child low fruit intake trajectory. Boys showed higher odds (OR 2.32; 95% CI 1.51, 3.68) of following the suboptimal fruit intake trajectory than girls. Children of mothers of Malay ethnicity, but not of Indian ethnicity, had higher odds of following the suboptimal fruit intake trajectory (OR 1.87; 95% CI 1.12, 3.06) than children of mothers of Chinese ethnicity. Every one-score increase in maternal pregnancy HEI-SGP (score range 0-100) was associated with lower odds (OR 0.98; 95% CI 0.97, 0.99) of children following the suboptimal fruit intake trajectory. Relative to children who were breastfed<6months, children who were breastfed for ≥6months had lower odds (OR 0.57; 95% CI 0.36, 0.92) of following the suboptimal fruit intake trajectory. Neither maternal education, pregnancy BMI, nor pregnancy smoking was directly associated with the child suboptimal fruit intake trajectory. Detailed results for all direct pathways are presented in Supplementary Tables 4 and 5.

The relative contributions of maternal and child factors were assessed by comparing the strength (magnitude of effect size: beta-coefficients and ORs) of the direct pathways. Child sex was found to be the strongest determinant of suboptimal fruit intake trajectory. Maternal ethnicity was a pivotal determinant as it was implicated in multiple pathways leading to child suboptimal fruit intake trajectory. Apart from a significant direct association, maternal ethnicity was also indirectly associated with the child suboptimal fruit intake trajectory via the mediating effect of maternal pregnancy diet quality. The association between maternal ethnicity (Malay vs. Chinese) and higher odds of following the child suboptimal fruit intake trajectory was partially mediated by maternal pregnancy diet quality, contributing to 11% of total effect (Table 2). Furthermore, maternal ethnicity also influenced multiple intermediate downstream factors including maternal education, BMI, and pregnancy smoking, all of which were linked to breastfeeding duration, which in turn was associated with the suboptimal fruit intake trajectory. In addition to the direct association, maternal pregnancy diet quality score was also indirectly associated with child suboptimal fruit intake trajectory via the mediating effect of breastfeeding duration. Breastfeeding duration (≥6 vs.<6 months) mediated 36% of the total effect between maternal pregnancy diet quality and lower odds of following the child suboptimal fruit intake trajectory (Table 2).

Table 1 Sample characteristics according to fruit and vegetable intake trajectory groups

	Fruit intake trajectory groups				Vegetable intake trajectory groups						
	Low stable to decreasing (n=137)		High stable (n=676)			High decreasing (n=98)		Low to stable (n=75)		Consistently high (n=644)		
	n	% or mean(SD)	n	% or mean(SD)	P-value	n	% or mean(SD)	n	% or mean(SD)	n	% or mean(SD)	P-value
Child sex					<0.001							0.005
Girls	45	32.8%	343	50.7%		34	34.7%	30	40.0%	324	50.6%	
Boys	92	67.2%	333	49.3%		64	65.3%	45	60.0%	316	49.4%	
Child birth weight (kg)	137	3.09(0.49)	676	3.10(0.47)	0.915	98	3.08(0.49)	75	3.10(0.45)	640	3.10(0.48)	0.951
Maternal age (years)	134	30.85(5.39)	657	31.47(5.04)	0.194	97	30.99(5.59)	71	29.69(5.79)	623	31.62(4.91)	0.008
Maternal BMI (kg/m²)	131	27.06(5.11)	642	26.01(4.29)	0.014	95	27.06(5.00)	68	27.47(5.18)	610	25.91(4.24)	0.003
Maternal smoking					0.003							<0.001
Non-smoker	107	79.9%	585	89.2%		81	83.5%	50	70.4%	561	90.2%	
Ex- or current-smoker	27	20.1%	71	10.8%		16	16.5%	21	29.6%	61	9.8%	
Maternal ethnicity					<0.001							<0.001
Chinese	61	44.5%	415	61.9%		47	48.5%	14	18.9%	415	65.2%	
Malay	61	44.5%	144	21.5%		41	42.3%	51	68.9%	113	17.8%	
Indian	15	11.0%	111	16.6%		9	9.3%	9	12.2%	108	17.0%	
Maternal education					0.001							<0.001
Secondary/lower	52	38.5%	181	27.4%		39	40.2%	40	55.6%	154	24.6%	
Post-secondary	54	40.0%	229	34.7%		41	42.3%	23	31.9%	219	35.0%	
University	29	21.5%	250	37.9%		17	17.5%	9	12.5%	253	40.4%	
Maternal pregnancy diet quality score	125	49.11(12.92)	604	53.30(13.81)	0.002	92	48.08(12.80)	65	47.65(13.50)	572	53.87(13.66)	<0.001
Breastfeeding duration					<0.001							<0.001
<6months	99	75.6%	363	56.4%		67	73.6%	56	82.4%	339	55.0%	
≥6months	32	24.4%	281	43.6%		24	26.4%	12	17.7%	277	45.0%	

BMI, body mass index; SD, standard deviation
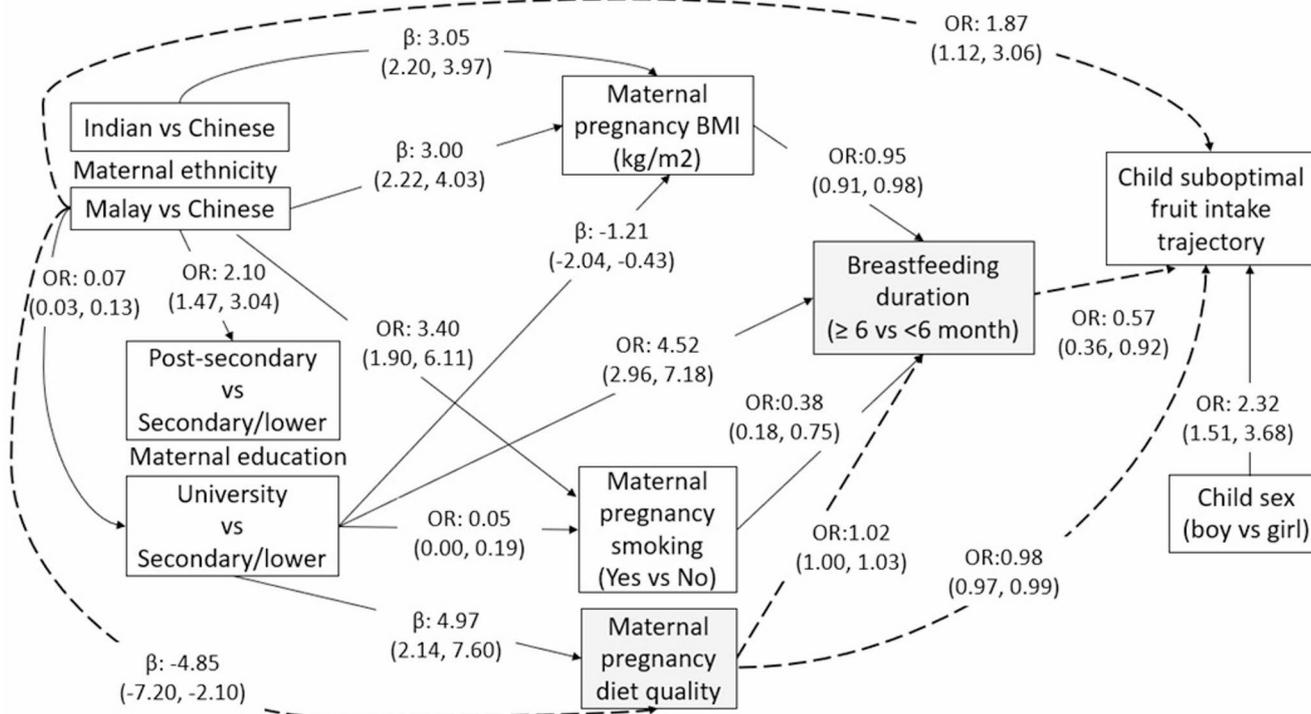
Fig. 2 Pathways (direct associations) linking maternal ethnicity, education, pregnancy smoking, pregnancy body mass index (BMI), pregnancy diet quality, child sex, and the child suboptimal 'Low stable to decreasing' vs. 'High stable' fruit intake trajectory group. Effect sizes of all direct pathways are shown as β (beta-coefficient) and OR (odds ratio) with 95% confidence intervals. Dotted lines represent mediation with variables in grey boxes as mediators

Direct and indirect pathways linking maternal and child factors and suboptimal vegetable intake trajectory

Given the small proportions of the 'High decreasing' and 'Low to stable' vegetable intake trajectory groups and largely similar sample characteristics, they were combined and collectively referred as the suboptimal intake group and compared with the 'Consistently high' vegetable intake group in GSEM. With respect to determinants of child suboptimal vegetable intake trajectory group **(**Fig. 3**)**, results were largely similar to those of fruit intake trajectories, with child sex (boys vs. girls OR 1.80; 95% CI 1.16, 2.81), maternal ethnicity (Malay vs. Chinese OR 3.49; 95% CI 2.14, 5.60) and pregnancy diet quality score (OR 0.97; 95% CI 0.96, 0.99) being identified as significant determinants. However, a borderline significant direct association (OR 0.65; 95% CI 0.40, 1.04) was observed for breastfeeding duration (≥6 vs. <6 months). Moreover, a significant direct association was found between maternal education and child suboptimal vegetable trajectory intake group. Children of mothers with university education (OR 0.47; 95% CI 0.24, 0.89), but not those with post-secondary education, had lower odds of following the suboptimal vegetable intake trajectory than children of mothers with secondary or lower education.

No evidence of direct associations was found for maternal pregnancy BMI and smoking with the child suboptimal vegetable intake trajectory.

With respect to the suboptimal vegetable intake trajectory and the relative influences of maternal and child factors, maternal ethnicity was the most influential factor both in terms of the strength of the direct pathway and its impact on multiple intermediate factors. Maternal ethnicity showed the strongest direct association, followed by child sex, maternal education and pregnancy diet quality. Maternal ethnicity was also associated with suboptimal vegetable intake trajectory via a sequential pathway through maternal education followed by pregnancy diet quality, which subsequently led to suboptimal vegetable intake trajectory. The association between maternal ethnicity (Malay vs. Chinese) and higher odds of following the child suboptimal vegetable intake trajectory was mediated by maternal education (60% of total effect) and maternal pregnancy diet quality (3% of total effect) (Table 2). Maternal pregnancy diet quality score also mediated 13% of the total effect between maternal education (university versus secondary/lower) and lower odds of following the child suboptimal vegetable intake trajectory (Table 2).

Table 2 Mediational pathways between maternal and child factors and child suboptimal fruit ('Low stable to decreasing') or vegetable ('High decreasing and low to Stable') intake trajectories

	Effect size	95% confidence interval
Maternal ethnicity (Malay vs. ref Chinese) and suboptimal fruit intake trajectory		
Direct effect	0.63	(0.11, 1.12)
Indirect effect via maternal pregnancy diet quality	0.08	(0.01, 0.18)
Total effect	0.70	(0.22, 1.22)
% mediation by maternal pregnancy diet quality	11%	
Maternal pregnancy diet quality and suboptimal fruit intake trajectory		
Direct effect	− 0.016	(− 0.030, − 0.001)
Indirect effect via breastfeeding duration	− 0.009	(− 0.023, − 0.001)
Total effect	− 0.025	(− 0.043, − 0.007)
% mediation by breastfeeding duration	36%	
Maternal ethnicity (Malay vs. ref Chinese) and suboptimal vegetable intake trajectory		
Direct effect	1.25	(0.76, 1.72)
Indirect effect via maternal education	2.00	(0.31, 3.93)
Indirect effect via maternal pregnancy diet quality	0.11	(0.03, 0.23)
Total effect	3.36	(1.75, 5.18)
% mediation by maternal education	60%	
% mediation by maternal pregnancy diet quality	3%	
Maternal education (University vs. ref Secondary and lower) and suboptimal vegetable intake trajectory		
Direct effect	− 0.76	(− 1.42, − 0.12)
Indirect effect via maternal pregnancy diet quality	− 0.11	(− 0.24, − 0.03)
Total effect	− 0.87	(− 1.51, − 0.25)
% mediation by maternal pregnancy diet quality	13%	

Effect sizes are presented as log-odds; 95% confidence interval (upper, lower)

Reference category for suboptimal 'Low stable to decreasing' fruit intake is 'High stable'

Reference category for suboptimal 'High decreasing and Low to Stable' vegetable intake is 'Consistently high'
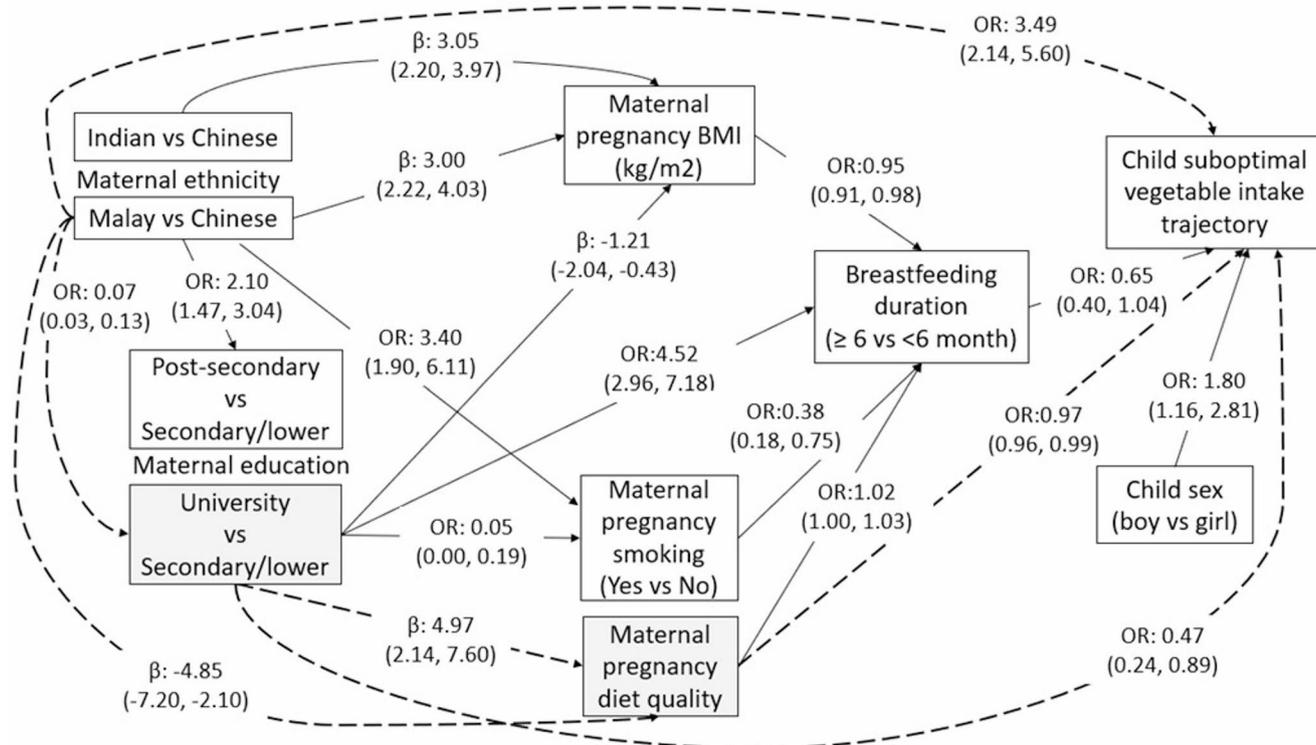
Fig. 3 Pathways (direct associations) linking maternal ethnicity, education, pregnancy smoking, pregnancy body mass index (BMI), pregnancy diet quality, child sex, and the child suboptimal 'High decreasing and Low to Stable' vs. 'Consistently high' vegetable intake trajectory group. Effect sizes of all direct pathways are shown as β (beta-coefficient) and OR (odds ratio) with 95% confidence intervals. Dotted lines represent mediation with variables in grey boxes as mediators

Discussion

In a longitudinal, multi-ethnic Asian cohort, distinct fruit and vegetable intake trajectories from toddlerhood to early adolescence were identified. Two fruit intake trajectories emerged: "High stable" and "Low stable to decreasing". Three vegetable intake trajectories were identified: "Consistently high," "High decreasing," and "Low to stable." Child sex, maternal ethnicity, and pregnancy diet quality were directly associated with suboptimal trajectories for fruit ("Low stable to decreasing") and vegetable ("High decreasing/Low to stable") intakes. A direct inverse association was observed for longer breastfeeding duration and the suboptimal child fruit intake trajectory, and for higher maternal education and the suboptimal child vegetable intake trajectory. Maternal ethnicity was the most influential determinant, having a direct association with suboptimal intake trajectories of fruit or vegetable while also exerting direct influences on multiple downstream factors (e.g., maternal education, pregnancy BMI, smoking status, diet quality) that in turn led to suboptimal intake trajectories of fruits and vegetables.

The present study is the first to examine respective fruit and vegetable intake trajectories from toddlerhood to adolescence. Our study revealed that distinct trajectories of fruit and vegetable intakes emerged from toddlerhood, making it unique from previous cohort studies in children which primarily examined changes in combined fruit and vegetable intake from late childhood (ages 8–10 years) until adolescence or early adulthood [24–27]. Of these, only one study examined intake trajectories, but it assessed joint trajectories with breakfast eating from childhood to adolescence [27]. Data from many countries have revealed a higher prevalence of inadequate vegetable intake than of fruit intake [4–6], highlighting the need to examine fruit and vegetable intakes separately. In line with our study findings, a UK study examining the changes in respective fruit and vegetable intakes from ages 2 to 23 years using four waves of national survey data also discovered a decline in fruit intake starting from age 7 years [28]. It is important to note that children from the 'High stable' or 'Consistently high' intake trajectory in our cohort consumed less fruits and vegetables than WHO or Singaporean dietary recommendations [3, 29], emphasizing the importance of promoting fruit and vegetable intakes from early life.

Expanding findings from previous studies that reported cross-sectional associations of maternal and child factors with fruit and vegetable intakes in childhood or adolescence [30–35], our study provides novel findings on the relative importance of these factors in influencing trajectories of fruit and vegetable intakes. No previous study has simultaneously assessed sequential direct and indirect pathways, providing valuable insights into the interplay of maternal and child factors and how they co-jointly influence child suboptimal fruit and vegetable intakes. Notably, maternal ethnicity was identified as the most pivotal distal factor influencing suboptimal fruit and vegetable intake trajectories as evidenced by a direct association as well as indirect associations via maternal education and/or pregnancy diet quality. Specifically, our mediation analyses showed that mothers of Malay ethnicity were more likely to have low maternal diet quality during pregnancy, which in turn led to increased risk of their child following the suboptimal fruit intake trajectory. Similar findings were found for vegetable intake trajectories, with maternal education being identified as an additional mediator underlying the association between maternal ethnicity and the suboptimal intake trajectory. Women with higher education are more likely to have better diet quality, which could promote positive parental modelling of healthy dietary intakes and home availability of healthy foods such as fruits and vegetables, resulting in better child dietary intakes [36]. In addition, maternal dietary intakes before and during pregnancy may affect child's food preferences by influencing a child's food flavour exposure in utero [37–39]. We also observed direct associations of maternal ethnicity with pregnancy diet quality, BMI and smoking, which were inversely linked with longer breastfeeding duration. Subsequently, longer breastfeeding duration decreased the risk of the child belonging to the suboptimal fruit and vegetable intake trajectories. Better diet quality, a healthy body weight status, and lower rate of smoking during pregnancy, as a proxy of a healthy lifestyle [40, 41], may promote good milk supply and promote longer duration of breastfeeding [42]. Breastfeeding may also shape children's appetite and food preferences via exposing infants to flavours through breastmilk [43].

Another key determinant of suboptimal fruit and vegetable intake trajectories was child sex, with boys being more likely to follow a suboptimal fruit or vegetable intake trajectory than girls. Similar gender differences in fruit and vegetable intakes have been reported previously [30]. It is hypothesized that females may have different taste preference and tend to prefer fruits and vegetables more than males [44]. In addition, females are more likely to be impacted by external influences (i.e., parental, peers, and social) and more receptive to dietary advice or more health conscious as they grow older, resulting in healthier dietary intakes (e.g., higher fruit and vegetable intakes) at older ages [45].

Our study has several strengths including being the first to examine early determinants of longitudinal trajectories of fruit and vegetable intakes from toddlerhood to early adolescence in an Asian multi-ethnic cohort. The repeated measurements of fruit and vegetable intakes enabled the use of GBTM to elucidate dynamic changes in fruit and vegetable

intakes over time. GBTM retains participants with partial data under missing-at-random assumptions, reducing attrition bias. The use of GSEM is another strength which allowed the simultaneous evaluation of the integrative pathways linking various maternal and child factors with fruit and vegetable intake trajectories, enabling quantification of both direct and indirect/mediational effects. GSEM also has potential to guide targeted interventions by identifying key factors that could be prioritized for intervention by assessing the relative contribution of various factors. The long duration of follow-up is another strength which enabled assessment of changes in fruits and vegetables from toddlerhood to early adolescence.

Limitations of our study include that varying numbers of fruit and vegetable items were captured by FFQs over four time points. Varying FFQ items and portion size estimation could introduce measurement error, and biomarker calibration was unavailable. We captured groups within the sample that had differential intake trajectories of fruit and vegetables over the four time points. While intake trajectories reflect relative patterns, absolute intake changes cannot be inferred. Additionally, dietary intake was self-reported by either mothers or children, and reporting bias cannot be dismissed. The excluded participants, compared with those included in the analysis, had characteristics associated with a higher likelihood of following the suboptimal fruit or vegetable intake trajectories (i.e., lower education, lower pregnancy diet quality, and shorter breastfeeding duration), potentially leading to underestimation of true effect sizes. Given the observational design of the study, casual inference cannot be drawn, and unmeasured/residual confounding is also possible. Lastly, mothers with post-secondary/university education comprised 70% of the sample, compared to 64% in the general Singaporean population [46], which may limit generalisability of study findings to the wider Singaporean population.

Conclusion

Children exhibited distinct trajectories of fruit and vegetable intakes from toddlerhood to adolescence. Most children (∼80%) followed a 'High stable' fruit intake or 'Consistently high' vegetable intake trajectory. The remaining children followed suboptimal low or declining trajectory of fruit or intake trajectories. Maternal ethnicity, pregnancy diet quality, education, breastfeeding duration and child sex were identified as determinants of suboptimal low or declining fruit or vegetable intake trajectories. Notably, children in the 'High' fruit and vegetable intake trajectories had intakes below recommendations, underscoring the urgency of interventions and public health initiatives to increase fruit and

vegetable intakes from early life. Such interventions should be initiated from preconception or pregnancy and prioritize Malay mothers, those with lower education, and improve maternal diet quality during pregnancy and promote breastfeeding. Moreover, such interventions should be carried forward until toddlerhood and adolescence, with enhanced strategies for families with boys.

Data availability Data described in the manuscript, code book, and analytic code will be made available upon request pending approval from our study executives.

Declarations

Conflict of interest The other authors declared no conflict of interest.

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References

1. Aune D, Giovannucci E, Boffetta P, Fadnes LT, Keum N, Norat T, Greenwood DC, Riboli E, Vatten LJ, Tonstad S (2017) Fruit and vegetable intake and the risk of cardiovascular disease, total cancer and all-cause mortality-a systematic review and dose-response meta-analysis of prospective studies. Int J Epidemiol 46(3):1029–1056. https://doi.org/10.1093/ije/dyw319

2. Hartley L, Igbinedion E, Holmes J, Flowers N, Thorogood M, Clarke A, Stranges S, Hooper L, Rees K (2013) Increased consumption of fruit and vegetables for the primary prevention of cardiovascular diseases. Cochrane Database Syst Rev 2013(6):CD009874. https://doi.org/10.1002/14651858.CD009874.pub2

3. World Health Organization (2023) Increasing fruit and vegetable consumption to reduce the risk of noncommunicable diseases. https://www.who.int/tools/elena/interventions/fruit-vegetables-ncds

4. Hamner HC, Dooyema CA, Blanck HM, Flores-Ayala R, Jones JR, Ghandour RM, Petersen R (2023) Fruit, vegetable, and sugar-sweetened beverage intake among young children, by state—United States, 2021. MMWR Morb Mortal Wkly Rep 72(7):165–170. https://doi.org/10.15585/mmwr.mm7207a1

5. Fayet-Moore F, McConnell A, Cassettari T, Tuck K, Petocz P, Kim J (2020) Vegetable intake in Australian children and adolescents: the importance of consumption frequency, eating occasion and its association with dietary and sociodemographic factors.

6. Rivera JA, Pedraza LS, Aburto TC, Batis C, Sanchez-Pimienta TG, Gonzalez de Cosio T, Lopez-Olmedo N, Pedroza-Tobias A (2016) Overview of the dietary intakes of the Mexican population: results from the National health and nutrition survey 2012. J Nutr 146(9):1851S–1855S. https://doi.org/10.3945/jn.115.221275

7. Ventura AK, Worobey J (2013) Early influences on the development of food preferences. Curr Biol 23(9):R401–408. https://doi.org/10.1016/j.cub.2013.02.037

8. Barker DJ (2007) The origins of the developmental origins theory. J Intern Med 261(5):412–417. https://doi.org/10.1111/j.1365-2796.2007.01809.x

9. Poston L, Godfrey KM, Gluckman PD, Hanson MA (2022) Developmental origins of health and disease. In: developmental origins of health and disease. 2 edn. Cambridge University Press, Cambridge, pp 1–7

10. Rasmussen M, Krolner R, Klepp KI, Lytle L, Brug J, Bere E, Due P (2006) Determinants of fruit and vegetable consumption among children and adolescents: a review of the literature. Part I: quantitative studies. Int J Behav Nutr Phys Act 3:22. https://doi.org/10.1186/1479-5868-3-22

11. Chong MF (2022) Dietary trajectories through the life course: opportunities and challenges. Br J Nutr 128(1):154–159. https://doi.org/10.1017/S0007114522001295

12. Soh SE, Tint MT, Gluckman PD, Godfrey KM, Rifkin-Graboi A, Chan YH, Stunkel W, Holbrook JD, Kwek K, Chong YS, Saw SM, Group GS (2014) Cohort profile: growing up in Singapore towards healthy outcomes (GUSTO) birth cohort study. Int J Epidemiol 43(5):1401–1409. https://doi.org/10.1093/ije/dyt125

13. Lim HX, Toh JY, Tan KH, Chong YS, Yap F, Godfrey KM, Lee YS, Chong MF (2019) Validation of a semi-quantitative FFQ for 18-month-old toddlers: the growing up in Singapore towards healthy outcomes (GUSTO) study. Public Health Nutr 22(11):1990–2000. https://doi.org/10.1017/S1368980019000557

14. Sugianto R, Chan MJ, Wong SF, Shek LP, Tan KH, Chong YS, Godfrey KM, Tai BC, Chong MF (2020) Evaluation of a quantitative food frequency questionnaire for 5-year-old children in an Asian population. J Acad Nutr Diet 120(3):437–444. https://doi.org/10.1016/j.jand.2019.09.021

15. Lai JS, Loh J, Toh JY, Sugianto R, Colega M, Tan KH, Yap FKP, Chong YS, Godfrey KM, Chong MF (2022) Evaluation of paper-based and web-based food frequency questionnaires for 7-year-old children in Singapore. Br J Nutr 128(8):1626–1637. https://doi.org/10.1017/S0007114521004517

16. Appannah G, Toh JY, Lai JS, Yong HY, Shariff ZM, Tint MT, Yuan WL, Pang WW, Godfrey KM, Tan KH, Yap F, Lee YS, Eriksson JG, Chong MFF (2024) Dietary pattern trajectories in early childhood and their associations with patterns of maternal feeding practices in a multi-ethnic Asian cohort. Nutr J 23(1):110. https://doi.org/10.1186/s12937-024-01012-5

17. Lai JS, Soh SE, Loy SL, Colega M, Kramer MS, Chan JKY, Tan TC, Shek LPC, Yap FKP, Tan KH, Godfrey KM, Chong YS, Chong MFF (2019) Macronutrient composition and food groups associated with gestational weight gain: the GUSTO study. Eur J Nutr 58(3):1081–1094. https://doi.org/10.1007/s00394-018-1623-3

18. Han CY, Colega M, Quah EPL, Chan YH, Godfrey KM, Kwek K, Saw SM, Gluckman P, Chong YS, Chong MF (2015) A healthy eating index to measure diet quality in pregnant women in singapore: a cross-sectional study. BMC Nutr. https://doi.org/10.1186/s40795-015-0029-3

19. Pang WW, Aris IM, Fok D, Soh SE, Chua MC, Lim SB, Saw SM, Kwek K, Gluckman PD, Godfrey KM, van Dam RM, Kramer MS, Chong YS, Group GS (2016) Determinants of breastfeeding

Public Health Nutr 23(3):474–487. https://doi.org/10.1017/S1368980019002090X

practices and success in a Multi-Ethnic Asian population. Birth 43(1):68–77. https://doi.org/10.1111/birt.12206

20. Nagin DS, Jones BL, Passos VL, Tremblay RE (2018) Group-based multi-trajectory modeling. Stat Methods Med Res 27(7):2015–2023. https://doi.org/10.1177/0962280216673085

21. Nagin DS (2014) Group-based trajectory modeling: an overview. Ann Nutr Metab 65(2–3):205–210. https://doi.org/10.1159/000360229

22. Rabe-Hesketh S, Skrondal A, Pickles A (2004) Generalized multilevel structural equation modeling. Psychometrika 69:167–190

23. Baron RM, Kenny DA (1986) The moderator-mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations. J Pers Soc Psychol 51(6):1173–1182

24. Larson NI, Neumark-Sztainer D, Hannan PJ, Story M (2007) Trends in adolescent fruit and vegetable consumption, 1999–2004: project EAT. Am J Prev Med 32(2):147–150. https://doi.org/10.1016/j.amepre.2006.10.011

25. Elinder LS, Heinemans N, Zeebari Z, Patterson E (2014) Longitudinal changes in health behaviours and body weight among Swedish school children–associations with age, gender and parental education–the SCIP school cohort. BMC Public Health 14:640. https://doi.org/10.1186/1471-2458-14-640

26. Lounassalo I, Hirvensalo M, Kankaanpaa A, Tolvanen A, Palomaki S, Salin K, Fogelholm M, Yang X, Pahkala K, Rovio S, Hutri-Kahonen N, Raitakari O, Tammelin TH (2019) Associations of leisure-time physical activity trajectories with fruit and vegetable consumption from childhood to adulthood: the cardiovascular risk in young Finns study. Int J Environ Res Public Health.https://doi.org/10.3390/ijerph16224437

27. Chen CY, Hsiao YC (2018) Dual trajectories of breakfast eating and fruit and vegetable intake over a 5-year follow-up period among economically disadvantaged children: gender differences. Appetite 121:41–49. https://doi.org/10.1016/j.appet.2017.10.027

28. Albani V, Butler LT, Traill WB, Kennedy OB (2017) Fruit and vegetable intake: change with age across childhood and adolescence. Br J Nutr 117(5):759–765. https://doi.org/10.1017/S0007114517000599

29. Health Promotion Board Ministry of Health Singapore Nutritious Foods For A Healthy Diet https://www.healthhub.sg/programmes/nutrition-hub/eat-more#home

30. Pearson N, Biddle SJ, Gorely T (2009) Family correlates of fruit and vegetable consumption in children and adolescents: a systematic review. Public Health Nutr 12(2):267–283. https://doi.org/10.1017/S1368980008002589

31. Stephens LD, McNaughton SA, Crawford D, Ball K (2014) Longitudinal predictors of frequent vegetable and fruit consumption among socio-economically disadvantaged Australian adolescents. Appetite 78:165–171. https://doi.org/10.1016/j.appet.2014.03.023

32. Hong SA, Piaseu N (2017) Prevalence and determinants of sufficient fruit and vegetable consumption among primary school children in Nakhon Pathom, Thailand. Nutr Res Pract 11(2):130–138. https://doi.org/10.4162/nrp.2017.11.2.130

33. Di Noia J, Monica D, Cullen KW, Perez-Escamilla R, Gray HL, Sikorskii A (2016) Differences in fruit and vegetable intake by race/ethnicity and by Hispanic origin and nativity among women in the special supplemental nutrition program for women, Infants, and Children, 2015. Prev Chronic Dis 13:E115. https://doi.org/10.5888/pcd13.160130

34. Noiman A, Lee SH, Marks KJ, Grap ME, Dooyema C, Hamner HC (2024) Factors associated with daily fruit and vegetable intakes among children aged 1–5 years in the united States. Nutrients. https://doi.org/10.3390/nu16050751

35. Chong KH, Lee ST, Ng SA, Khouw I, Poh BK (2017) Fruit and vegetable intake patterns and their associations with sociodemographic characteristics, anthropometric status and nutrient intake profiles among Malaysian children aged 1–6 years. Nutrients. https://doi.org/10.3390/nu9080723

36. Lwin MO, Malik S, Lau J (2020) Association between food availability and young people's fruits and vegetables consumption: understanding the mediation role of the theory of planned behaviour. Public Health Nutr 23(12):2155–2164. https://doi.org/10.1017/S1368980019005263

37. Mennella JA, Beauchamp GK (1991) Maternal diet alters the sensory qualities of human milk and the nursling's behavior. Pediatrics 88(4):737–744

38. Mennella JA, Jagnow CP, Beauchamp GK (2001) Prenatal and postnatal flavor learning by human infants. Pediatrics 107(6):E88. https://doi.org/10.1542/peds.107.6.e88

39. Dalrymple KV, Vogel C, Godfrey KM, Baird J, Hanson MA, Cooper C, Inskip HM, Crozier SR (2023) Evaluation and interpretation of latent class modelling strategies to characterise dietary trajectories across early life: a longitudinal study from the Southampton women's survey. Br J Nutr 129(11):1945–1954. https://doi.org/10.1017/S000711452200263X

40. Holahan CJ, Holahan CK, Lim S, Powers DA (2021) Living with a smoker and multiple health-risk behaviors. Ann Behav Med 55(4):287–297. https://doi.org/10.1093/abm/kaaa059

41. Lucini D, Zanuso S, Blair S, Pagani M (2015) A simple healthy lifestyle index as a proxy of wellness: a proof of concept. Acta Diabetol 52(1):81–89. https://doi.org/10.1007/s00592-014-0605-z

42. Talebi S, Kianifar HR, Mehdizadeh A (2024) Nutritional requirements in pregnancy and lactation. Clin Nutr ESPEN 64:400–410. https://doi.org/10.1016/j.clnesp.2024.10.155

43. Ventura AK (2017) Does breastfeeding shape food preferences? Links to obesity. Ann Nutr Metab 70 Suppl 3:8–15. https://doi.org/10.1159/000478757

44. Lombardo M, Feraco A, Armani A, Camajani E, Gorini S, Strollo R, Padua E, Caprio M, Bellia A (2024) Gender differences in body composition, dietary patterns, and physical activity: insights from a cross-sectional study. Front Nutr 11:1414217. https://doi.org/10.3389/fnut.2024.1414217

45. Feraco A, Armani A, Amoah I, Guseva E, Camajani E, Gorini S, Strollo R, Padua E, Caprio M, Lombardo M (2024) Assessing gender differences in food preferences and physical activity: a population-based survey. Front Nutr 11:1348456. https://doi.org/10.3389/fnut.2024.1348456

46. Singapore Department of Statistics (2024) Educational profile of Singapore residents aged 25 years and over, 2000–2024. Singapore Department of Statistics. https://www.singstat.gov.sg/find-data/search-by-theme/population/education-language-spoken-and-literacy/latest-data. Accessed 27 October 2025

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