PLOS | ONE

RESEARCH ARTICLE

Multi-behavioral obesogenic phenotypes among school-aged boys and girls along the birth weight continuum

Andre Krumel Portella[1,2]*, **Catherine Paquet**[3], **Adrianne Rahde Bischoff**[4], **Roberta Dalle Molle**[5], **Aida Faber**[1], **Spencer Moore**[6], **Narendra Arora**[7], **Robert Levitan**[8,9], **Patricia Pelufo Silveira**[10,11,12], **Laurette Dube**[1]

1 Desautels Faculty of Management, McGill Center for the Convergence of Health and Economics, McGill University, Montreal, QC, Canada, **2** PostGraduate Program in Pediatrics, Universidade Federal de Ciencias da Saude de Porto Alegre, Porto Alegre, RS, Brasil, **3** School of Health Sciences, Centre for Population Health Research, University of South Australia, Adelaide, South Australia, Australia, **4** Division of Neonatology, Department of Pediatrics, University of Toronto, Toronto, ON, Canada, **5** Programa de Pós-Graduação em Saúde da Criança e do Adolescente, Faculdade de Medicina, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil, **6** Arnold School of Public Health, University of South Carolina, Columbia, SC, United States of America, **7** The INCLEN Trust, New Delhi, India, **8** Institute of Medical Science, University of Toronto, Toronto, ON, Canada, **9** Centre for Addiction and Mental Health (CAMH), Toronto, ON, Canada, **10** Department of Psychiatry, Faculty of Medicine, McGill University, Montreal, QC, Canada, **11** Sackler Institute for Epigenetics & Psychobiology, McGill University, Montreal, QC, Canada, **12** Ludmer Centre for Neuroinformatics and Mental Health, Douglas Hospital Research Centre, Montreal, QC, Canada

* andre.portella@mcgill.ca

Abstract

Evidence shows that extremes of birth weight (BW) carry a common increased risk for the development of adiposity and related cardiovascular diseases, but little is known about the role of obesogenic behaviors in this process. Moreover, no one has empirically examined whether the relationship between BW, obesogenic behaviors and BMI along the full low-to-high birthweight continuum reflects the U-shape pattern expected from common risk at both BW extremes. Our objective was to characterize physical activity, screen time, and eating behavior and their relationship to BMI as a function of BW among school-aged boys and girls. In this cross-sectional study, 460 children aged 6 to 12 years (50% boys) from Montreal, Canada provided information on sleeping time, screen time, physical activity levels, eating behavior (emotional, external and restrained eating) and anthropometrics (height, weight, BW) through parent reported questionnaires. BMI was normalized using WHO Standards (zBMI), and BW expressed as ratio using Canadian population standards (BW for gestational age and sex). Analyses were conducted using generalized linear models with linear and quadratic terms for BW, stratified by sex and adjusted for age, ethnicity and household income. In boys, physical activity and screen time showed U-shaped associations with BW, while physical activity had an inverted U-shaped in girls. Emotional and restrained eating had positive linear relations with BW in boys and girls. Sleep time and external eating were not associated with BW. A U-shaped relationship between BW and zBMI was found in boys but no association was found in girls. Only sleep (in boys and girls), and emotional eating (girls only) were related to zBMI and mediation of the BW-zBMI relationship was only

OPEN ACCESS

Citation: Portella AK, Paquet C, Bischoff AR, Molle RD, Faber A, Moore S, et al. (2019) Multi-behavioral obesogenic phenotypes among school-aged boys and girls along the birth weight continuum. PLoS ONE 14(2): e0212290. https://doi.org/10.1371/journal.pone.0212290

Editor: Kathleen M. Hill Gallant, Purdue University, UNITED STATES

Received: October 24, 2018

Accepted: January 30, 2019

Published: February 21, 2019

Copyright: © 2019 Portella et al. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: A minimal anonymized data set necessary to replicate our study findings is made available online in the Supporting Information files.

Funding: This study was supported by Canadian Institutes of Health Research (CIHR); http://www.cihr-irsc.gc.ca/; CIHR-India grant ref no. INC 110726 (LB, SM and NA). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

supported for emotional eating. In conclusion, BW relates to obesogenic behaviors and BMI in both non-linear and linear ways, and these associations differed by sex.

Introduction

Both extremes of the birth weight normal distribution have been associated with higher incidence of later life chronic diseases and conditions such as increased adiposity, metabolic syndrome, dyslipidemia, and cardiovascular disease[1–3]. Although the literature has extensively explored this relationship in terms of the programming of metabolic functions[4, 5], there is also emerging evidence for the early-life programming of behavioral phenotypes such as physical activity[6, 7], feeding preferences[8], and sleep patterns[9].

Low birth weight individuals, for instance, have been found to have food preferences biased towards highly caloric, highly palatable foods[10–12], be more impulsive towards a sweet reward[13], have decreased sensitivity to the enjoyment of the sweet taste[14, 15], and also exercise less[16, 17]. In contrast, much less evidence is available for the impact of high birth weight on behavior in human research. We have recently reported a negative correlation between birth weight and preference for fat in the habitual dietary intake of 6–12 years boys, and Ester et al[18]showed at high birth weight children scored higher on food approach and lower on food avoidant scales. Animal models suggest a similar pattern of behavioral alterations[16, 17, 19, 20]. In general, boys and girls differ both at the neurological and biological levels in terms of timing of fat rebound, puberty, and body composition [21], and these facts ultimately influence feeding behavior [22, 23]. Therefore, while prenatal programming seems to modify eating patterns of both boys and girls when compared to controls, the timing and nature of the differences can vary between the sexes during development [23–25].

Behavior plays a critical role in the determination of obesity, especially physical activity[26], screen time[27, 28], eating behavior[29] and sleep habits[30]. Moreover, the clustering of more than one energy balance-related behavioral risk factor is known to be more deleterious to health than a single factor alone in both children[31–35] and adults[36, 37]. While those behaviors have been frequently investigated in the literature, to the best of our knowledge no study has investigated then together in the same sample in relationship to birth weight and sex.

The above evidence opens the possibility for the existence of a more complex expression of the low and high birth weight phenotypes. These individuals would not only have a Metabolic Thrifty Phenotype, expressed by their increased adiposity deposition with consequent higher cardiometabolic risk, as proposed by Barker et al[38, 39], but also what we are calling a Thrifty Eating or Thrifty Behavior Phenotype. This would be characterized by an increase in the intake of palatable foods and decrease energy expenditure in favor of a positive energy balance[13]. Obesity and cardiometabolic risk in this population would hence be a result not only of peripheral metabolic adaptations, but also from concomitant altered behaviors acting as mediators or adjuvants of these effects.

In the present study, we aimed to further explore this hypothesis by characterizing the associations between birth weight and different obesogenic behaviors across the sexes: screen time [40], physical activity[41], eating behavior[42] and sleep[30], elucidating possible points for more effective behavioral interventions aimed at both treatment and prevention.

Methods

A sample of households from the Montreal Metropolitan area was selected from a large database of families who previously indicated their willingness to participate in academic research and were likely to have children in the targeted age group (6–12 years old). These families were contacted by telephone by an independent research firm and invited to take part in a survey about children's eating and lifestyle habits on behalf of the researchers from McGill University. This survey was part one of a multi-component Brain-to-Society diagnostic study aiming to map children's behaviors with regards to a multitude of factors, including their environment, eating habits, physical activity, and body mass indexes (BMI). Questionnaires were completed by children's parents or guardians.

Respondents were first asked whether there were any children aged 6–12 years who lived in their households most of the time (>50% of the time in a regular week). If yes, the interviewer then proceeded to ask to speak with the parent or guardian who knew the child's daily habits best. If more than one child between 6–12 years old was residing within the household, the parent/guardian was asked to answer all questions regarding the child who had the next birthday. Verbal consent was obtained from all participants who were mailed a $10 check for completing the 50-minute telephonic survey. Data collection was conducted between March and August 2013 and received ethical approval from McGill University's Institutional Research Board(A09-M15-12A). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Measures

The survey included household demographic information, children's anthropometrics (height and weight), and web-based questionnaires on sleeping, screen time (TV, computer) and physical activity time, and eating behavior. The eating behavior questionnaire was adapted from the Dutch Eating Behavior Questionnaire (DEBQ)[43], and was reported by the parents or caregiver. The questions were re-worded for parents to report on their child's behavior and adapted to fit the cultural context and improve suitability for children. For instance, the term delicious was replaced for "yummy" and food sources like cafes replaced for corner stores ('dépanneur'). The number of response options were also changed from five to three consistent with previous adaptations of the scale for children [44]. Internal consistency of this scale for the sample, assessed following the approach recommended by Gadermann and colleagues [45] for estimating reliability coefficients for ordinal data, was found to be within the acceptable to good range for external (Cronbach's Alpha = 0.74) and emotional (Cronbach's Alpha = 0.86) eating, although near acceptable for restrained eating (0.67)[42, 44, 46]. Sleep Time (hours per night) was obtained from the Children's Sleep Habits Questionnaire[47]. Sports, Play, and Active Recreation for Kids (SPARK) Questionnaire developed by Sallis et al.[48] and questions from the School Health Action Planning and Evaluation Systems (SHAPES) Survey[49] were used to measure physical activity and screen time. Questions included a 7-day recall of how many hours and minutes the child had spent on vigorous and/or moderate physical activity and activities involving a screen. Examples of both vigorous and moderate physical activity and screen activities were detailed in the questionnaire and responses were asked for each day of the week.

The behavioral outcomes were Emotional, Restrained and External eating scores from the DEBQ questionnaire[46], physical activity (minutes per week), screen time (minutes per week) and hours of sleep (hours per night). The anthropometric outcome, BMI, was calculated following the formula weight(Kg)/height $(cm)^2$, and normalized to age and sex (z-score) using WHO growth standards and methodology[50]. To normalize birth weight(g) to gestational age, sex for populational standards, we utilized the Birth Weight Ratio (BWR), that is the ratio between the infant birthweight and the sex-specific mean birthweight for each gestational age in weeks for the local population[51, 52].

Statistical methods

The first set of analyses tested associations between BWR and behavioral outcomes across sexes. Physical activity, screen time, emotional eating and dietary restraint were all positively skewed and modelled using Poisson models; sleep time and external eating were modelled using linear regression. A second set of analyses tested the associations between BWR and zBMI before and after inclusion of the individual behaviors. For behaviors for which statistically significant associations were found with both BWR and zBMI, a formal mediation test using bootstrapping was conducted in MPLUS Version 8 (Los Angeles, CA: Muthén & Muthén). Birth Weight Ratio (BWR) was treated as a continuous variable and mean-centered prior to analyses. Baseline characteristic were analyzed using BWR divided in tertiles and One-Way ANOVA (Age) and Chi-square (Income and Ethnicity) was applied to the sample stratified by sex. To explore potential u-shaped relationships between BWR and outcomes linear and quadratic terms for BWR were included in all models. All models were adjusted for age, sex ethnicity and household income categorized into three categories (< 45,000; 45,000 to 65,000; >65,000 CAD). As stated in the introduction, we expect sex differences in obesity related behavioral factors, therefore sex-stratified analyses where conducted. Analyses were performed using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). In all analyses, statistical significance was set at 0.05.

Results

Data were available for 460 children (230 boys and 230 girls). Characteristics of the sample are presented in Table 1 by birth weight tertiles.

Associations between birth weight and behavior

Results of analyses testing associations between BWR and health behaviors are reported in Table 2. Main effects results suggested the presence of curvilinear relationships between BWR and physical activity and screen time as indicated by significant quadratic terms. Emotional

Table 1. Characteristics of the sample.

	Boys (n = 230)							Girls (n = 230)						
BWR Tertile (range)	**Lower (0.54 to 0.94)**		**Middle (0.95 to 1.08)**		**Upper (1.09 to 1.54)**			**Lower (0.65 to 0.94)**		**Middle (0.95 to 1.08)**		**Upper (1.09 to 1.76)**		
	n = 78		**n = 74**		**n = 78**		**p-value**	**n = 76**		**n = 80**		**n = 74**		**p-value**
Income (%)														
>65K / year	52	(34.7%)	50	(33.3%)	48	(32.0%)	-	48	(32.4%)	49	(33.1%)	51	(34.5%)	-
45K to 65k / year	10	(28.6%)	10	(28.6%)	15	(33.3%)	-	15	(33.3%)	21	(46.7%)	9	(20.0%)	-
<45k / year	16	(35.6%)	14	(31.1%)	15	(33.3%)	0.815^a	13	(35.1%)	10	(27.0%)	14	(37.8%)	0.255^a
Age (SD)	9.1	(1.7)	9.3	(1.6)	9.3	(1.7)	0.540^b	9.1	(1.7)	8.8	(1.7)	9.0	(1.7)	0.556^b
Ethnicity														
Canadian	66	(84.6%)	64	(86.5%)	62	(79.5%)	-	58	(76.3%)	64	(80.0%)	63	(85.1%)	-
Other	12	(15.4%)	10	(13.5%)	16	(20.5%)	0.482^a	18	(23.7%)	16	(20.0%)	11	(14.9%)	0.393^a

SD: standard deviation.

[a] Pearson Chi-Square.

[b] One-Way ANOVA.

https://doi.org/10.1371/journal.pone.0212290.t001

Table 2. Results of analyses testing associations between birth weight ratio (BWR) and behaviors stratified by sex.

Predictor		Physical Activity (95%CI)		Screen Time (95%CI)		Sleep Estimate(95%CI)	
		BOYS	GIRLS	BOYS	GIRLS	BOYS	GIRLS
BWR		-0.21 (-0.23,-0.18)***	0.01 (0.07,0.13)***	0.04 (0.01,0.018)**	<0.01 (-0.03,0.04)	-0.20 (-0.89,0.50)	-0.16 (-0.86,0.53)
BWR*BWR		0.50 (0.40,0.60)***	-0.26 (-0.35,-0.17)***	.96 (1.85,2.07)***	0.64 (0.54,0.74)***	-1.25 (-3.96,1.45)	-0.37 (-2.28,1.82)
age		-0.01 (-0.01,-0.01)***	-0.07 (-0.07,-0.07)***	0.10 (0.10,0.10)***	0.05 (0.05,0.05)***	-0.15 (-0.22,-0.08)***	-0.21 (-0.28,-0.15)
Household income (> 65K as reference group)	<45	-0.03 (-0.04,-0.02)***	0.05 (0.03,0.06)***	-0.04 (-0.05,-0.02)***	0.12 (0.11,0.14)***	-0.35 (-0.66,-0.04)*	-0.10 (-0.41,0.20)
	45-65K	-0.14 (-0.17,-0.13)***	-0.02 (-0.03,-0.01)**	0.22 (0.21,0.24)***	0.07 (0.05,0.08)***	-0.17 (-0.51,0.16)	-0.02 (-0.25,0.31)
Ethnicity		-0.05 (-0.06,-0.03)***	0.10 (0.09,0.12)***	0.08 (0.07,0.10)***	-0.39 (-0.41,-0.37)***	0.01 (-0.32,0.34)	-0.40 (-0.67,-0.12)**
		Emotional eating (95%CI)		**Restrained eating (95%CI)**		**External eating (95%CI)**	
		BOYS	**GIRLS**	**BOYS**	**GIRLS**	**BOYS**	**GIRLS**
BWR		1.23 (0.67,1.80)***	2.88 (2.16,3.60)***	1.45 (0.84,2.06)***	1.27 (0.60,1.95)**	-0.56 (-3.36,2.24)	3.30 (-0.05,6.65)
BWR*BWR		0.91 (-1.11,2.94)	-3.29 (-5.10,-1.48)**	1.35 (-0.81,3.51)	-1.90 (3.87,0.06)	3.60 (-7.28,14.48)	-2.65 (-12.37,7.07)
age		0.17 (0.11,1.23)***	0.08 (0.02,0.13)*	0.09 (0.03,0.16)**	0.19 (0.13,0.25)***	0.05 (-0.24,0.34)	-0.39 (-0.71,-0.08)*
Household income (> 65K as reference group)	<45	1.02 (0.79,1.23)***	0.01 (-0.24,0.27)	0.31 (0.06,0.56)*	0.10 (-0.17,0.37)	0.82 (-0.44,2.08)	0.62 (-0.82,2.07)
	45-65K	0.84 (0.60,1.08)***	0.30 (0.08,0.52)**	0.18 (-0.10,0.46)	0.35 (0.12,059)**	1.03 (-0.32,2.38)	-0.25 (-1.60,1.10)
Ethnicity		0.23 (0.00,0.45)*	0.42 (0.21,0.63)***	0.34 (0.10,0.59)**	0.54 (0.32,0.75)***	1.45 (0.13,2.77)*	1.04 (-0.28,2.36)

Physical activity, screen time, emotional eating and dietary restraint were modelled using Poisson models. Screen time and external eating were modelled using linear regression

*<0.05

**<0.01

***<0.0001

https://doi.org/10.1371/journal.pone.0212290.t002

and restrained eating were found to be mostly linearly related to BWR. No statistically significant associations were found for sleep and external eating measures. Interactions between BWR terms and sex indicated significant interactions for physical activity, screen time, emotional and restrained eating. Fitted curves for boys and girls are shown in Fig 1. A U-shape relationship between BWR and physical activity was found for boys, in which lower BWR boys had the highest physical activity scores. This relationship was inverted for girls, with girls on either extreme of the BWR distribution having lower physical activity scores compared to girls with moderate BWR. A U-shape relationship was also found for screen time in boys, with screen time being highest in boys with higher birth weight ratios. This U-shape relationship was also found in girls, but with reduced magnitude. Sex-specific results for emotional and restrained eating suggested a mostly linear relationship between eating behaviors and BWR in boys. The same relationships were found to follow an inverted U-shape relationship in girls.

Associations between birth weight ratio, obesogenic behaviors and BMI

Results of analyses testing the association between BWR and zBMI (reported in Table 2) suggest that the relationship was curvilinear and statistically significant with evidence of gender

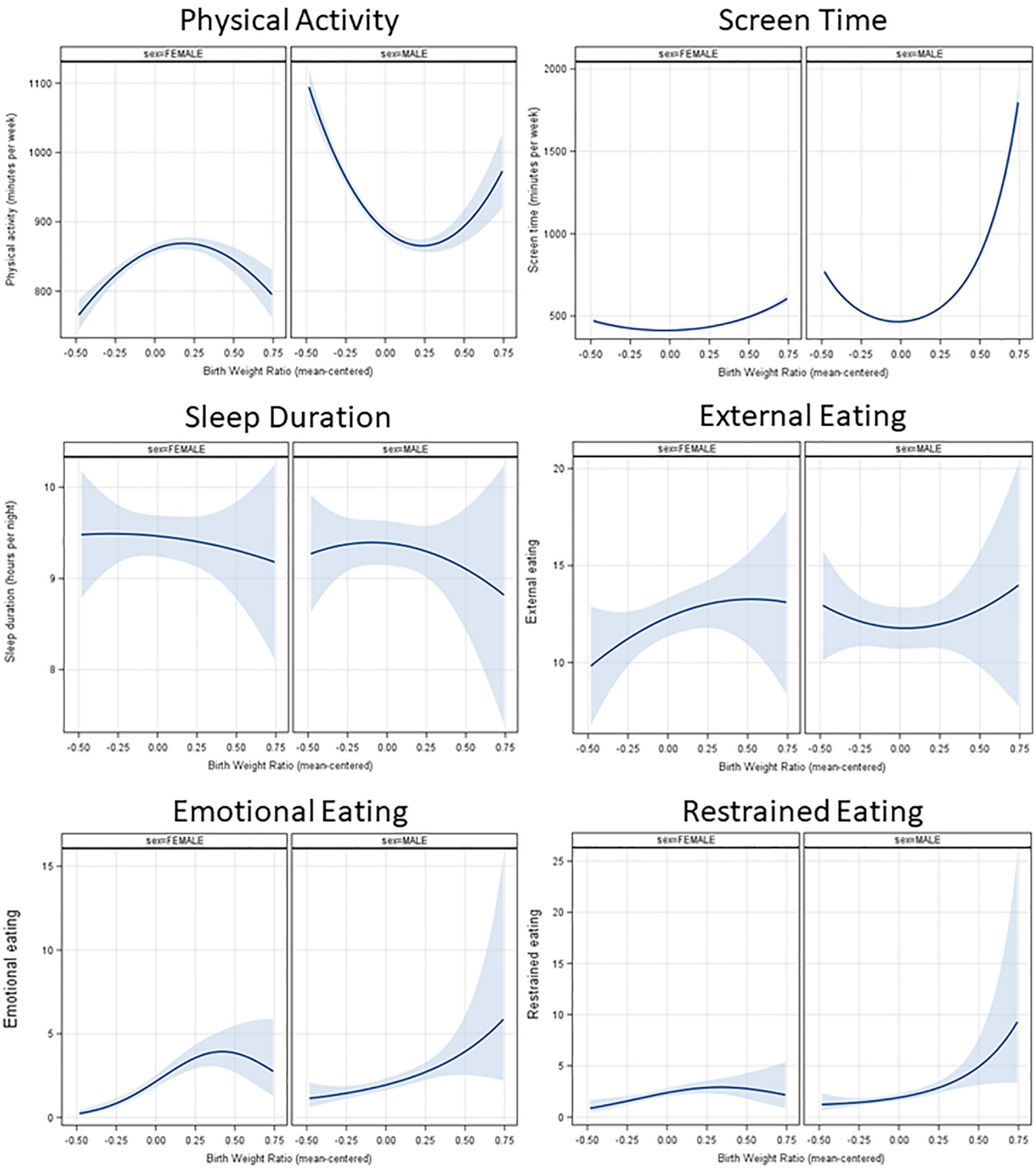

Fig 1. Fitted curves between birth weight ratio and health behaviors by sex. Figure showing fitted curves between Birth Weight Ratio and health behaviors by sex.

https://doi.org/10.1371/journal.pone.0212290.g001

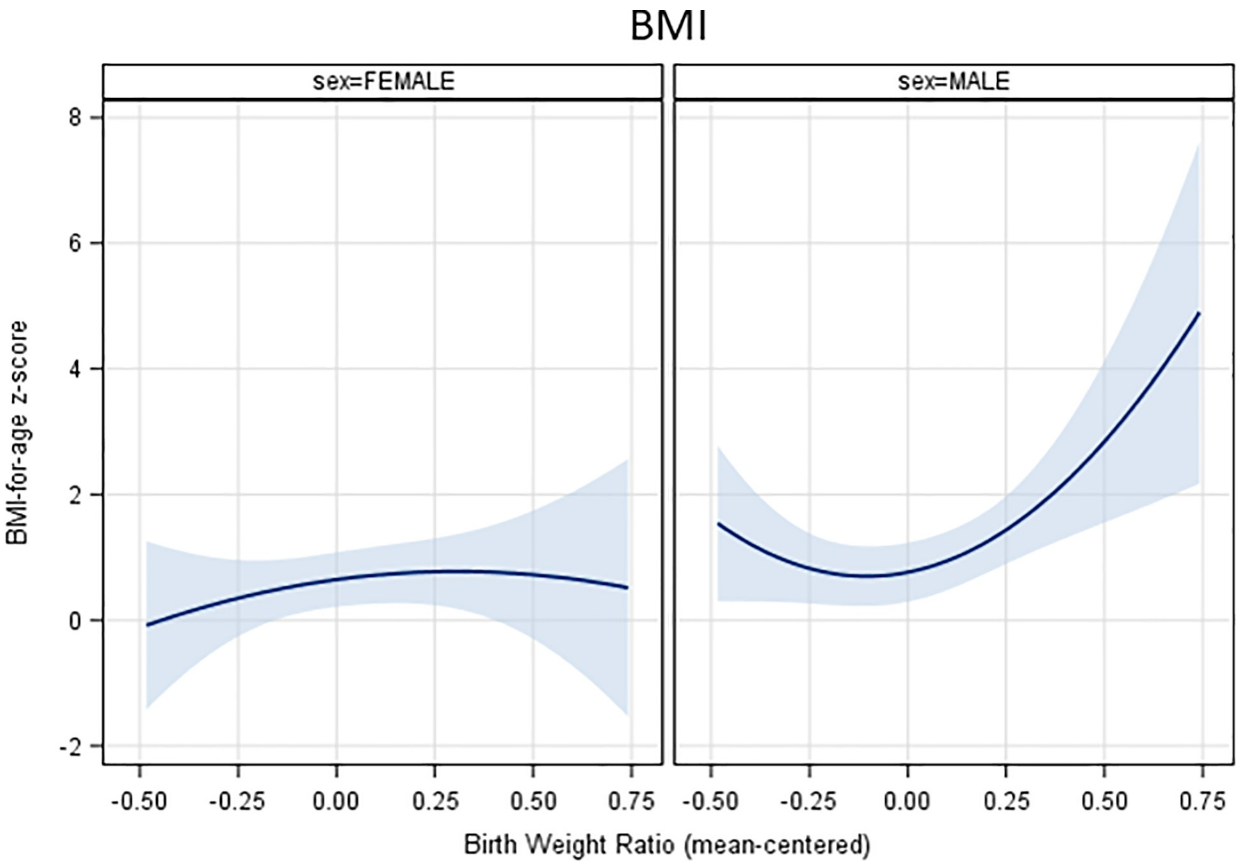

Fig 2. Fitted curves between birth weight ratio and zBMI in boys and girls.

https://doi.org/10.1371/journal.pone.0212290.g002

differences in the relationship. Sex-specific fitted curves and analyses (presented in Fig 2 and Table 3, respectively) indicated that the relationship was statistically significant and U-shaped in boys, with zBMI being highest in boys with high BWR, but relatively flat and non-significant for girls. Individual behaviors were added to the zBMI model (see Table 3) to explore potential mediation by behaviors. Only sleep (in boys and girls), and emotional and restrained eating (girls only) were found to be related to zBMI. Given that sleep was not related to BWR, only mediation by emotional and restrained eating in girls was tested. Results of indirect (mediated) effect testing using bootstrapping of the associations between both the linear and quadratic terms of BWR on zBMI through emotional and restrained eating suggested a possible mediation of the linear BWR term through emotional eating (Indirect effect: 0.345; 95%CI = 0.062, 0.629; P = 0.017). None of the other indirect effects reached statistical significance (P-values > 0.12).

Discussion

In this study we have found some distinct patterns of association between the continuum of birth weight and childhood obesogenic behaviors considering linear and quadratic distributions and sex[53]. Birth weight effects were more evident in boys, as compared to girls, especially for physical activity and screen time. These sex differences in behaviors and obesity risk are expected, and most certainly related to the many neurobiological dissimilarities between boys and girls—especially in terms of fat rebound timing, puberty, and differential growth

Table 3. Results of models (estimates (95% CI)) testing associations between birth weight ratio and zBMI accounting for individual behaviors, by sex.

		No behavior		Physical Activity		Screen time		Sleep	
		BOYS	GIRLS	BOYS	GIRLS	BOYS	GIRLS	BOYS	GIRLS
BWR		1.25 (-0.06,2.56)	0.83 (-0.54,2.21)	1.22 (-0.08,2.54)	0.84 (-0.54,2.22)	1.24 (-0.06,2.56)	0.83 (-0.54,2.20)	1.18 (-0.11,2.48)	0.77 (-0.57,2.13)
BWR*BWR		6.07 (0.98,11.16)*	-1.23 (-5.22,2.76)	6.13 (1.04,11.21)*	-1.24 (-5.25,2.77)	6.07 (0.94,11.21)*	-1.41 (-5.39,2.57)	5.68 (0.65,10.70)*	-1.36 (-5.30,2.56)
Behavior		-	-	<0.01 (0.00,0.00)	0.00 (0.00,0.00)	<0.01 (0.00,0.00)	<0.01 (0.00,0.00)	-0.31 (-0.55,-0.07)*	-0.37 (-0.64,-0.15)**
age		0.02 (-0.12,0.15)	-0.02 (-0.15,0.11)	-0.02 (-0.12,0.15)	-0.02 (-0.15,0.11)	0.02 (-0.12,0.16)	-0.03 (-0.16,0.10)	-0.03 (-0.17,0.11)	-0.10 (-0.24,0.04)
Household income (> 65K as reference group)	<45	0.85 (0.16,1.34)*	0.09 (-0.50,0.69)	0.74 (0.15,1.33)	0.09 (-0.50,0.69)	0.75 (0.16,1.34)*	0.06 (-0.53,0.66)	0.64 (0.05,1.22)*	0.05 (-0.53,0.64)
	45-65K	0.49 (-0.14,1.12)	0.32 (-0.24,0.87)	0.47 (-0.16,1.11)	0.31 (-0.24,0.87)	0.49 (-0.15,1.12)	0.30 (-0.25,0.85)	0.43 (-0.19,1.06)	0.32 (-0.22,0.87)
ethnicity		0.40 (-0.22,1.01)	0.46 (-0.09,1.00)	0.39 (-0.22,1.00)	0.46 (-0.08,1.01)	0.39 (-0.22,1.01)	0.54 (-0.01,1.08)	0.40 (-0.21,1.00)	0.31 (-0.23,0.85)
Predictor				**Emotional eating**		**Restrained eating**		**External eating**	
				BOYS	**GIRLS**	**BOYS**	**GIRLS**	**BOYS**	**GIRLS**
BWR				1.16 (-0.16,2.47)	0.25 (-1.12,1.62)	1.02 (-0.30,2.34)	0.66 (-0.72,2.03)	1.24 (-0.07,2.55)	0.71 (-0.66,2.10)
BWR*BWR				5.96 (0.88,11.04)*	-0.82 (-4.71,3.06)	5.68 (1.62,10.75)*	-0.98 (-4.95,2.99)	6.10 (1.01,11.20)*	-1.13 (-5.19,2.85)
Behavior				0.03 (-0.03,0.10)	0.12 (0.06,0.18)***	0.08 (-0.01,0.17)	0.08 (-0.01,0.17)	-0.01 (-0.07,0.05)	0.03 (-0.02,0.09)
age				0.01 (-0.13,0.15)	-0.04 (-0.16,0.09)	0.01 (-0.13,0.14)	-0.05 (-0.18,0.08)	0.02 (-0.12,0.15)	-0.01 (-0.14,0.12)
Household income (> 65K as reference group)	<45			0.66 (0.06,1.27)*	0.09 (-0.49,0.67)	0.69 (0.11,1.28)*	0.08 (-0.52,0.67)	0.75 (0.16,1.35)*	0.10 (-0.50,0.70)
	45-65K			0.43 (-0.21,1.07)	0.24 (-0.31,0.78)	0.46 (-0.16,1.09)	0.26 (-0.30,0.81)	0.50 (-0.14,1.13)	0.32 (-0.23,0.88)
ethnicity				-0.37 (-0.24,0.99)	-0.35 (-0.18,0.88)	-0.34 (-0.28,0.95)	-0.37 (-0.18,0.91)	-0.41 (-0.21,1.03)	-0.42 (-0.13,0.96)

Physical activity, screen time, emotional eating and dietary restraint were modelled using Poisson models. Time and external eating were modelled using linear regression

*<0.05

**<0.01

***<0.0001

https://doi.org/10.1371/journal.pone.0212290.t003

patterns[21]—and gender associated effects, where physical activity is generally found to higher in boys[54, 55], especially when considering high intensity activities[56]. On the other hand, screen time has been less associated with sex differences[27, 28].

In analyzing the associations with BMI, we found that BMI had a u-shaped relationship with birth weight in boys. Several studies have indicated that high birth weight is associated with subsequently higher levels of body weight or obesity in childhood [57, 58], nevertheless, the evidence for a u-shaped (both extremes of birth weight) [59] or for the low birth weight side alone are more scarce[10]. One possible explanation could that low birth weight individuals have overall smaller bodies and the decreased lean mass would compensate the BMI increase[60]. Nevertheless, for the same BMI, the low birth weight individuals usually have more cardiometabolic complications[61, 62]. There is also some evidence suggesting an increased susceptibility to the beneficial effects of physical activity in the low birth weight individuals. Laaksonen et al. observed that a low size at birth was associated with hyperinsulinemia only in less active men[63], and likewise, Eriksson et al. found that they were strongly protected from glucose intolerance by regular exercise[64].

In boys both physical activity and screen time had a non-linear, U-Shaped distribution, meaning the extremes of the birth weight spectrum had higher reported physical activity and screen time. While increased physical activity is associated with better anthropometric and metabolic outcomes[27, 65], the increased screen time is associated with opposite effects[28]. This could represent a compensatory move, where increased sedentary time occurs in response to the excess energy expenditure related to physical activity, although some studies have shown that children can have high levels of both[26, 66], and that the mechanisms involved on the association between screen time and obesity may be not related to energy expenditure, but due to altered eating habits with increased intake of energy dense snacks and dinking more sugared drinks[67, 68]. Girls had the opposite direction for physical activity, but a similar pattern for screen time. As discussed above, the expression of sedentary/activity behavior may be sex-specific, a fact corroborated by Shakir et al, where sedentary behavior (video game playing) was positively related to obesity only in boys[69]. The effect on physical activity in girls, assumes an inverted U-shaped form, which is in the expected direction, especially taking into account the evidence that low birth weight individuals have reduced physical performance, including alterations in muscle mass and strength, muscle endurance and lower aerobic fitness later in life [60, 70–77]. Brutsaert *et al*, for instance, showed clear deficits in muscle strength and fatigue resistance in college-aged women with low ponderal index at birth[78]. Alterations in physical capacity may lead to reduced levels of physical activity[79, 80]. Screen time has been identified not only as a risk factor for obesity [1], but also for neurodevelopmental[2], psychological[3], behavioral and feeding alterations[4]. It has been reported also that neurocognitive functions are predictors of future patterns of weight gain in prospective studies [5], while compliance to healthier behaviors has been shown to be associated with a higher global cognition outcome[2]. The mutual influence of such factors makes the inference of causality very difficult, and even point-out to the possibility of mutual reciprocal effects, or perhaps still unidentified mediators

In terms of eating behavior, the association with birth weight assumed a more linear relationship, with emotional and restrained eating being positively related with birth weight. Emotional overeating refers to a tendency to overeat in response to negative emotions[81]. Findings on the relationship between emotional overeating and overweight are controversial. Some studies found no correlation[29, 82, 83], while others found a correlation with increased weight[84–87] as well as increased body fat percentage, waist and hip circumference[87]. Cortisol cord blood levels are similar in small and high birth weight individuals[88], but emotional eaters may have altered cortisol reactivity to stress, which induces overeating[89]. Restrained eating is defined as an attempted restriction of food intake[90]. Snoek *et al* showed a positive relationship between overweight and restrained eating in adolescents[29] and similar findings have been reported by others[82, 83]. Our results are in accordance to those described above and could explain the increased risk that children with higher birth weight have of becoming overweight in the future. One possible mechanism for such alteration might be related to alteration of the mesocorticolimbic dopaminergic pathways involved in the control of appetite[91, 92]. In fact, Eisenstein et al found that emotional eating was associated with striatal dopamine D2/D3 binding[93] and Volkow et al found that striatal dopamine response to foods was associated with restrained and emotional eating but not to external eating[94]. Also, in animal research, early life overnutrition has been found to increase dopaminergic precursors and to affect appetite for palatable foods[95, 96], similarly for prenatal undernutrition[11, 12, 97]. In general, low birth weight girls/women seem to be more vulnerable to the effects of prenatal programming of food preferences, showing increased preference for carbohydrates, impulsivity for sugar and emotional overeating when compared no normal birth weight counterparts [10, 13, 98]. However, other studies do not seem to find a sex effect[99], and in a subsample of the same cohort, we found a negative correlation between fat intake and BWR in boys, suggesting an increased preference for fat in the low birth weight side[19]. Therefore, while prenatal programming seems to modify eating patterns of both boys and girls when compared to controls, the timing and nature of the differences can vary between the sexes[24], fluctuating according to the adiposity rebound and body fat distribution during development [23].

Extensive literature from animal research has showed important effects of early life low and high birth weights on feeding behavior, appetite and physical activity[12, 95, 100–103]. A recent systematic review addressing the effects of birth weight on energetic metabolism associated behaviors in humans, such as physical activity, energetic intake, and some aspects of feeding behavior[104], did not find much evidence in the literature for such associations, except for decreased physical activity levels in both extremes of birth weight. However, this review did not explore the effects of birth weight on eating behaviors like feeding preferences, as measured by a differential intake of macronutrients, energy density or specific group of foods–such as fruits and vegetables—which is the most common finding in humans[10, 105, 106].

Sleep, eating behavior and cardiovascular control are closely related. It is known that birth weight, besides the influence on obesity and cardiovascular function, also influences the development of adequate sleeping patterns[9, 107]. Sleep is also associated to feeding behavior[108], adiposity[109], and metabolism[110, 111]. Such multidirectional effects have suggested a possible mediation pathway for sleeping into determining obesity, but in our case the number of sleeping hours was only associated with BMI, not birth weight.

Taking together, our results could suggest that, despite the similar risk for obesity and related diseases, Low and High birthweight individuals from different sexes might be cruising toward different pathways, making the identification of these differences critical for a more precise medical approach towards both prevention and treatment. Our study rises important findings about the relationship between birth weight and obesity, by including altered behavior in the equation. Moreover, the positive mediation found in this study places these altered feeding behavior as a candidate to be in the causal pathway towards obesity in this population. One possible mechanism for such alteration might be related to alteration of the mesocorticolimbic dopaminergic pathways involved in the control of appetite[91, 92].

Our study, nevertheless, has some limitations that have to be accounted for in the interpretations of the results. This is a cross-sectional analysis, therefore the relationships are associative, not causative. Our data analysis also treated the behaviors in isolation and future research should try to explore their interrelationship. The data collected are based in self-reported questionnaires, that although validated and carefully collected, always leave some potential for bias. Self-reported BMI is generally biased towards underreporting of obesity[112, 113], although in our case it would favor the null hypothesis. Moreover, especially in small sample sizes or underpowered studies, accuracy is more critical for categorization or clinical diagnosis, than it is for correlations. Our birth weight means, for instance, deviates only 1.6% for males and 3.3% for females from the average Canadian birth weights, normalized to gestational age and sex, while for BMI z-scores, are similar to contemporary research in Canada[114, 115]. The subscale restrained eating of the DEBQ questionnaire had an internal consistency of 0.67, which is slightly below the cutoff for acceptable, but emotional and external eating were in the acceptable range(0.86 and 0.74 respectively). Although our findings are not a definitive and conclusive response to the question, they rise important considerations about the different mechanisms involved in the pathway to obesity, highlighting the importance of behavioral, and individual brain eating responses to emotions and self-control in relationship to birthweight.

In summary, boys and girls born on the extremes of the normal range of birth weight are showing different phenotypical expression of behaviors while sharing the same risk of obesity. Therefore, the early life programming of vulnerability to obesogenic behaviors may take gender-specific behavioral causal pathways, opening perspectives of investigation, and prompting to the identification new strategic opportunities for prevention and treatment to yield better targeted prevention and treatment.

Supporting information

S1 File. Anonymized dataset.
(ZIP)

Author Contributions

Conceptualization: Andre Krumel Portella, Catherine Paquet, Roberta Dalle Molle, Aida Faber, Spencer Moore, Narendra Arora, Laurette Dube.

Data curation: Laurette Dube.

Formal analysis: Andre Krumel Portella, Catherine Paquet, Adrianne Rahde Bischoff, Roberta Dalle Molle, Robert Levitan, Patricia Pelufo Silveira.

Funding acquisition: Aida Faber, Spencer Moore, Narendra Arora, Laurette Dube.

Investigation: Catherine Paquet, Roberta Dalle Molle, Laurette Dube.

Methodology: Andre Krumel Portella, Adrianne Rahde Bischoff, Aida Faber, Narendra Arora, Robert Levitan, Laurette Dube.

Project administration: Aida Faber, Narendra Arora, Laurette Dube.

Resources: Spencer Moore, Narendra Arora, Laurette Dube.

Supervision: Patricia Pelufo Silveira, Laurette Dube.

Writing – original draft: Andre Krumel Portella, Patricia Pelufo Silveira.

Writing – review & editing: Andre Krumel Portella, Catherine Paquet, Adrianne Rahde Bischoff, Roberta Dalle Molle, Aida Faber, Spencer Moore, Narendra Arora, Robert Levitan, Patricia Pelufo Silveira, Laurette Dube.

References

1. Murtaugh MA, Jacobs DR, Jr., Moran A, Steinberger J, Sinaiko AR. Relation of birth weight to fasting insulin, insulin resistance, and body size in adolescence. Diabetes Care. 2003; 26(1):187–92. Epub 2002/12/28. PMID: 12502679.
2. Stansfield BK, Fain ME, Bhatia J, Gutin B, Nguyen JT, Pollock NK. Nonlinear Relationship between Birth Weight and Visceral Fat in Adolescents. J Pediatr. 2016; 174:185–92. Epub 2016/05/14. https://doi.org/10.1016/j.jpeds.2016.04.012 PMID: 27174144; PubMed Central PMCID: PMCPMC5711485.
3. Tam CH, Wang Y, Luan J, Lee HM, Luk AO, Tutino GE, et al. Non-linear relationship between birthweight and cardiometabolic risk factors in Chinese adolescents and adults. Diabet Med. 2015; 32(2):220–5. Epub 2014/11/13. https://doi.org/10.1111/dme.12630 PMID: 25388749.
4. Fowden AL, Forhead AJ. Endocrine mechanisms of intrauterine programming. Reproduction. 2004; 127(5):515–26. Epub 2004/05/07. https://doi.org/10.1530/rep.1.00033 PMID: 15129007.
5. Jones RH, Ozanne SE. Fetal programming of glucose-insulin metabolism. Mol Cell Endocrinol. 2009; 297(1–2):4–9. Epub 2008/07/30. https://doi.org/10.1016/j.mce.2008.06.020 PMID: 18662742.

6. Tikanmaki M, Tammelin T, Vaarasmaki M, Sipola-Leppanen M, Miettola S, Pouta A, et al. Prenatal determinants of physical activity and cardiorespiratory fitness in adolescence—Northern Finland Birth Cohort 1986 study. BMC Public Health. 2017; 17(1):346. Epub 2017/04/22. https://doi.org/10.1186/s12889-017-4237-4 PMID: 28427374; PubMed Central PMCID: PMCPMC5399469.
7. Kajantie E, Strang-Karlsson S, Hovi P, Raikkonen K, Pesonen AK, Heinonen K, et al. Adults born at very low birth weight exercise less than their peers born at term. J Pediatr. 2010; 157(4):610–6, 6 e1. Epub 2010/05/25. https://doi.org/10.1016/j.jpeds.2010.04.002 PMID: 20493499.
8. Dalle Molle R, Bischoff AR, Portella AK, Silveira PP. The fetal programming of food preferences: current clinical and experimental evidence. J Dev Orig Health Dis. 2015:1–9. Epub 2015/09/29. https://doi.org/10.1017/S2040174415007187 PMID: 26412563.
9. Yiallourou SR, Wallace EM, Miller SL, Horne RS. Effects of intrauterine growth restriction on sleep and the cardiovascular system: The use of melatonin as a potential therapy? Sleep Med Rev. 2016; 26:64–73. Epub 2015/07/05. https://doi.org/10.1016/j.smrv.2015.04.001 PMID: 26140865.
10. Barbieri MA, Portella AK, Silveira PP, Bettiol H, Agranonik M, Silva AA, et al. Severe intrauterine growth restriction is associated with higher spontaneous carbohydrate intake in young women. Pediatr Res. 2009; 65(2):215–20. Epub 2008/12/03. https://doi.org/10.1203/PDR.0b013e31818d6850 PMID: 19047956.
11. Alves MB, Dalle Molle R, Desai M, Ross MG, Silveira PP. Increased palatable food intake and response to food cues in intrauterine growth-restricted rats are related to tyrosine hydroxylase content in the orbitofrontal cortex and nucleus accumbens. Behav Brain Res. 2015; 287:73–81. Epub 2015/03/23. https://doi.org/10.1016/j.bbr.2015.03.019 PMID: 25796489.
12. Dalle Molle R, Laureano DP, Alves MB, Reis TM, Desai M, Ross MG, et al. Intrauterine growth restriction increases the preference for palatable foods and affects sensitivity to food rewards in male and female adult rats. Brain Res. 2015; 1618:41–9. Epub 2015/05/27. https://doi.org/10.1016/j.brainres.2015.05.019 PMID: 26006109.
13. Silveira PP, Agranonik M, Faras H, Portella AK, Meaney MJ, Levitan RD, et al. Preliminary evidence for an impulsivity-based thrifty eating phenotype. Pediatr Res. 2012; 71(3):293–8. Epub 2012/01/27. https://doi.org/10.1038/pr.2011.39 PMID: 22278183.
14. Ayres C, Agranonik M, Portella AK, Filion F, Johnston CC, Silveira PP. Intrauterine growth restriction and the fetal programming of the hedonic response to sweet taste in newborn infants. International journal of pediatrics. 2012; 2012:657379. https://doi.org/10.1155/2012/657379 PMID: 22851979; PubMed Central PMCID: PMC3407636.
15. Laureano DP, Molle RD, Portella AK, Silveira PP. Facial Expressions in Small for Gestational Age Newborns. J Child Neurol. 2016; 31(3):398–9. Epub 2015/07/02. https://doi.org/10.1177/0883073815592225 PMID: 26129978.
16. Cunha Fda S, Dalle Molle R, Portella AK, Benetti Cda S, Noschang C, Goldani MZ, et al. Both food restriction and high-fat diet during gestation induce low birth weight and altered physical activity in adult rat offspring: the "Similarities in the Inequalities" model. PLoS One. 2015; 10(3):e0118586. Epub 2015/03/05. https://doi.org/10.1371/journal.pone.0118586 PMID: 25738800; PubMed Central PMCID: PMCPMC4349804.
17. Fernandes FS, Portella AK, Barbieri MA, Bettiol H, Silva AA, Agranonik M, et al. Risk factors for sedentary behavior in young adults: similarities in the inequalities. J Dev Orig Health Dis. 2010; 1(4):255–61. Epub 2010/08/01. https://doi.org/10.1017/S204017441000019X PMID: 25141873.
18. Ester WA, Jansen PW, Hoek HW, Verhulst FC, Jaddoe VW, Marques AH, et al. Fetal size and eating behaviour in childhood: a prospective cohort study. Int J Epidemiol. 2018. Epub 2018/12/07. https://doi.org/10.1093/ije/dyy256 PMID: 30508111.
19. Bischoff AR, Portella AK, Paquet C, Dalle Molle R, Faber A, Arora N, et al. Low birth weight is associated with increased fat intake in school-aged boys. Br J Nutr. 2018; 119(11):1295–302. Epub 2018/05/18. https://doi.org/10.1017/S0007114518000892 PMID: 29770761.
20. Plagemann A. Perinatal nutrition and hormone-dependent programming of food intake. Horm Res. 2006; 65 Suppl 3:83–9. Epub 2006/04/14. https://doi.org/10.1159/000091511 PMID: 16612119.
21. Eisenmann JC, Heelan KA, Welk GJ. Assessing body composition among 3- to 8-year-old children: anthropometry, BIA, and DXA. Obes Res. 2004; 12(10):1633–40. Epub 2004/11/13. https://doi.org/10.1038/oby.2004.203 PMID: 15536227.
22. de Beer M, Vrijkotte TG, Fall CH, van Eijsden M, Osmond C, Gemke RJ. Associations of infant feeding and timing of linear growth and relative weight gain during early life with childhood body composition. Int J Obes (Lond). 2015; 39(4):586–92. Epub 2014/12/02. https://doi.org/10.1038/ijo.2014.200 PMID: 25435256.

23. Koyama S, Sairenchi T, Shimura N, Arisaka O. Association between timing of adiposity rebound and body weight gain during infancy. J Pediatr. 2015; 166(2):309–12. Epub 2014/12/03. https://doi.org/10.1016/j.jpeds.2014.10.003 PMID: 25454934.

24. Dulloo AG, Jacquet J, Seydoux J, Montani JP. The thrifty 'catch-up fat' phenotype: its impact on insulin sensitivity during growth trajectories to obesity and metabolic syndrome. Int J Obes (Lond). 2006; 30 Suppl 4:S23–35. Epub 2006/11/30. https://doi.org/10.1038/sj.ijo.0803516 PMID: 17133232.

25. Lanfer A, Knof K, Barba G, Veidebaum T, Papoutsou S, de Henauw S, et al. Taste preferences in association with dietary habits and weight status in European children: results from the IDEFICS study. Int J Obes (Lond). 2012; 36(1):27–34. Epub 2011/08/17. https://doi.org/10.1038/ijo.2011.164 PMID: 21844876.

26. Must A, Tybor DJ. Physical activity and sedentary behavior: a review of longitudinal studies of weight and adiposity in youth. Int J Obes (Lond). 2005; 29 Suppl 2(S2):S84–96. Epub 2005/12/31. PMID: 16385758.

27. Anderson SE, Economos CD, Must A. Active play and screen time in US children aged 4 to 11 years in relation to sociodemographic and weight status characteristics: a nationally representative cross-sectional analysis. BMC Public Health. 2008; 8(1):366. Epub 2008/10/24. https://doi.org/10.1186/1471-2458-8-366 PMID: 18945351; PubMed Central PMCID: PMCPMC2605460.

28. De Jong E, Visscher T, HiraSing R, Heymans M, Seidell J, Renders C. Association between TV viewing, computer use and overweight, determinants and competing activities of screen time in 4-to 13-year-old children. International journal of obesity. 2013; 37(1):47. https://doi.org/10.1038/ijo.2011.244 PMID: 22158265

29. Snoek HM, van Strien T, Janssens JM, Engels RC. Emotional, external, restrained eating and overweight in Dutch adolescents. Scand J Psychol. 2007; 48(1):23–32. Epub 2007/01/30. https://doi.org/10.1111/j.1467-9450.2006.00568.x PMID: 17257366.

30. Cappuccio FP, Taggart FM, Kandala NB, Currie A, Peile E, Stranges S, et al. Meta-analysis of short sleep duration and obesity in children and adults. Sleep. 2008; 31(5):619–26. Epub 2008/06/04. PMID: 18517032; PubMed Central PMCID: PMCPMC2398753.

31. Gubbels JS, Kremers SP, Stafleu A, Goldbohm RA, de Vries NK, Thijs C. Clustering of energy balance-related behaviors in 5-year-old children: lifestyle patterns and their longitudinal association with weight status development in early childhood. The international journal of behavioral nutrition and physical activity. 2012; 9:77. Epub 2012/06/23. https://doi.org/10.1186/1479-5868-9-77 PMID: 22721567; PubMed Central PMCID: PMCPMC3441251.

32. Gubbels JS, Kremers SP, Goldbohm RA, Stafleu A, Thijs C. Energy balance-related behavioural patterns in 5-year-old children and the longitudinal association with weight status development in early childhood. Public Health Nutr. 2012; 15(8):1402–10. Epub 2011/11/30. https://doi.org/10.1017/S1368980011003089 PMID: 22124196.

33. Cameron AJ, Crawford DA, Salmon J, Campbell K, McNaughton SA, Mishra GD, et al. Clustering of obesity-related risk behaviors in children and their mothers. Annals of epidemiology. 2011; 21(2):95–102. Epub 2010/12/28. https://doi.org/10.1016/j.annepidem.2010.11.001 PMID: 21184950.

34. Seghers J, Rutten C. Clustering of multiple lifestyle behaviours and its relationship with weight status and cardiorespiratory fitness in a sample of Flemish 11- to 12-year-olds. Public Health Nutr. 2010; 13 (11):1838–46. Epub 2010/03/20. https://doi.org/10.1017/S1368980010000418 PMID: 20236562.

35. Gubbels JS, Kremers SP, Stafleu A, Dagnelie PC, de Vries SI, de Vries NK, et al. Clustering of dietary intake and sedentary behavior in 2-year-old children. J Pediatr. 2009; 155(2):194–8. Epub 2009/04/28. https://doi.org/10.1016/j.jpeds.2009.02.027 PMID: 19394036.

36. Kremers SPJ, De Bruijn G-J, Schaalma H, Brug J. Clustering of energy balance-related behaviours and their intrapersonal determinants. Psychol Health. 2004; 19(5):595–606. https://doi.org/10.1080/0887044042331279630 WOS:000224989800004.

37. Schuit AJ, van Loon AJ, Tijhuis M, Ocke M. Clustering of lifestyle risk factors in a general adult population. Prev Med. 2002; 35(3):219–24. Epub 2002/08/31. PMID: 12202063.

38. Hales CN, Barker DJ. Type 2 (non-insulin-dependent) diabetes mellitus: the thrifty phenotype hypothesis. Diabetologia. 1992; 35(7):595–601. Epub 1992/07/01. PMID: 1644236.

39. Barker DJ, Eriksson JG, Forsen T, Osmond C. Fetal origins of adult disease: strength of effects and biological basis. Int J Epidemiol. 2002; 31(6):1235–9. Epub 2003/01/24. PMID: 12540728.

40. Sigmund E, Sigmundova D, Badura P, Kalman M, Hamrik Z, Pavelka J. Temporal Trends in Overweight and Obesity, Physical Activity and Screen Time among Czech Adolescents from 2002 to 2014: A National Health Behaviour in School-Aged Children Study. Int J Environ Res Public Health. 2015; 12 (9):11848–68. Epub 2015/09/24. https://doi.org/10.3390/ijerph120911848 PMID: 26393638; PubMed Central PMCID: PMCPMC4586711.

41. Hobbs M, Griffiths C, Green MA, Jordan H, Saunders J, McKenna J. Associations between the combined physical activity environment, socioeconomic status, and obesity: a cross-sectional study. Perspect Public Health. 2018; 138(3):169–72. Epub 2017/12/28. https://doi.org/10.1177/1757913917748353 PMID: 29281499.

42. Carnell S, Wardle J. Measuring behavioural susceptibility to obesity: validation of the child eating behaviour questionnaire. Appetite. 2007; 48(1):104–13. Epub 2006/09/12. https://doi.org/10.1016/j.appet.2006.07.075 PMID: 16962207.

43. Paquet C, de Montigny L, Labban A, Buckeridge D, Ma Y, Arora N, et al. The moderating role of food cue sensitivity in the behavioral response of children to their neighborhood food environment: a cross-sectional study. The international journal of behavioral nutrition and physical activity. 2017; 14(1):86. Epub 2017/07/07. https://doi.org/10.1186/s12966-017-0540-9 PMID: 28679391; PubMed Central PMCID: PMCPMC5499022.

44. van Strien T, Oosterveld P. The children's DEBQ for assessment of restrained, emotional, and external eating in 7- to 12-year-old children. Int J Eat Disord. 2008; 41(1):72–81. Epub 2007/07/20. https://doi.org/10.1002/eat.20424 PMID: 17634965.

45. Gadermann AM, Guhn M, Zumbo BDJPA, Research, Evaluation. Estimating ordinal reliability for Likert-type and ordinal item response data: A conceptual, empirical, and practical guide. 2012; 17 (3):1–13.

46. Van Strien T, Frijters JE, Bergers GP, Defares PB. The Dutch Eating Behavior Questionnaire (DEBQ) for assessment of restrained, emotional, and external eating behavior. International journal of eating disorders. 1986; 5(2):295–315.

47. Owens JA, Spirito A, McGuinn M. The Children's Sleep Habits Questionnaire (CSHQ): psychometric properties of a survey instrument for school-aged children. Sleep. 2000; 23(8):1043–51. Epub 2001/01/06. PMID: 11145319.

48. Sallis JF, Condon SA, Goggin KJ, Roby JJ, Kolody B, Alcaraz JE. The development of self-administered physical activity surveys for 4th grade students. Research quarterly for exercise and sport. 1993; 64(1):25–31. Epub 1993/03/01. https://doi.org/10.1080/02701367.1993.10608775 PMID: 8451530.

49. Leatherdale ST, Manske S, Wong SL, Cameron R. Integrating research, policy, and practice in school-based physical activity prevention programming: the School Health Action, Planning, and Evaluation System (SHAPES) Physical Activity Module. Health Promot Pract. 2009; 10(2):254–61. Epub 2008/02/22. https://doi.org/10.1177/1524839906298499 PMID: 18287582.

50. World Health Organization. Child growth standards. Accessed from http://wwwwhoint/childgrowth/software/en/. 2011.

51. Kramer MS, Platt RW, Wen SW, Joseph KS, Allen A, Abrahamowicz M, et al. A new and improved population-based Canadian reference for birth weight for gestational age. Pediatrics. 2001; 108(2): E35. Epub 2001/08/03. PMID: 11483845.

52. Kramer MS, Platt R, Msc HY, McNamara H, Usher RH. Are All Growth-restricted Newborns Created Equal(ly)? Pediatrics. 1999; 103(3):599–602. https://doi.org/10.1542/peds.103.3.599 WOS:000078960100011. PMID: 10049963

53. Bischoff AR, Pokhvisneva I, Léger É, Gaudreau H, Steiner M, Kennedy JL, et al. Dynamic interaction between fetal adversity and a genetic score reflecting dopamine function on developmental outcomes at 36 months. PloS one. 2017; 12(5):e0177344. https://doi.org/10.1371/journal.pone.0177344 PMID: 28505190

54. Trost SG, Pate RR, Sallis JF, Freedson PS, Taylor WC, Dowda M, et al. Age and gender differences in objectively measured physical activity in youth. Med Sci Sports Exerc. 2002; 34(2):350–5. Epub 2002/02/06. 11828247. PMID: 11828247

55. Sallis JF, Prochaska JJ, Taylor WC. A review of correlates of physical activity of children and adolescents. Med Sci Sports Exerc. 2000; 32(5):963–75. Epub 2000/05/05. PMID: 10795788.

56. Sallis JF, Zakarian JM, Hovell MF, Hofstetter CR. Ethnic, socioeconomic, and sex differences in physical activity among adolescents. Journal of clinical epidemiology. 1996; 49(2):125–34. PMID: 8606313

57. Schellong K, Schulz S, Harder T, Plagemann A. Birth weight and long-term overweight risk: systematic review and a meta-analysis including 643,902 persons from 66 studies and 26 countries globally. PLoS One. 2012; 7(10):e47776. Epub 2012/10/20. https://doi.org/10.1371/journal.pone.0047776 PMID: 23082214; PubMed Central PMCID: PMCPMC3474767.

58. Yu ZB, Han SP, Zhu GZ, Zhu C, Wang XJ, Cao XG, et al. Birth weight and subsequent risk of obesity: a systematic review and meta-analysis. Obes Rev. 2011; 12(7):525–42. Epub 2011/03/29. https://doi.org/10.1111/j.1467-789X.2011.00867.x PMID: 21438992.

59. Charles MA, Pettitt DJ, McCance DR, Hanson RL, Bennett PH, Knowler WC. Gravidity, obesity, and non-insulin-dependent diabetes among Pima Indian women. The American journal of medicine. 1994; 97(3):250–5. Epub 1994/09/01. 0002-9343(94)90008-6 [pii]. PMID: 8092174.

60. Yliharsila H, Kajantie E, Osmond C, Forsen T, Barker DJ, Eriksson JG. Birth size, adult body composition and muscle strength in later life. Int J Obes (Lond). 2007; 31(9):1392–9. Epub 2007/03/16. https://doi.org/10.1038/sj.ijo.0803612 PMID: 17356523.

61. Whincup PH, Kaye SJ, Owen CG, Huxley R, Cook DG, Anazawa S, et al. Birth weight and risk of type 2 diabetes: a systematic review. JAMA. 2008; 300(24):2886–97. Epub 2008/12/26. https://doi.org/10.1001/jama.2008.886 PMID: 19109117.

62. Forsen T, Eriksson J, Tuomilehto J, Reunanen A, Osmond C, Barker D. The fetal and childhood growth of persons who develop type 2 diabetes. Ann Intern Med. 2000; 133(3):176–82. Epub 2000/07/25. PMID: 10906831.

63. Laaksonen DE, Lakka HM, Lynch J, Lakka TA, Niskanen L, Rauramaa R, et al. Cardiorespiratory fitness and vigorous leisure-time physical activity modify the association of small size at birth with the metabolic syndrome. Diabetes Care. 2003; 26(7):2156–64. Epub 2003/07/02. PMID: 12832329.

64. Eriksson JG, Yliharsila H, Forsen T, Osmond C, Barker DJ. Exercise protects against glucose intolerance in individuals with a small body size at birth. Prev Med. 2004; 39(1):164–7. Epub 2004/06/23. https://doi.org/10.1016/j.ypmed.2004.01.035 PMID: 15207998.

65. Abril V, Manuel-y-keenoy B, Sola R, Garcia JL, Nessier C, Rojas R, et al. Prevalence of overweight and obesity among 6-to 9-year-old school children in Cuenca, Ecuador: relationship with physical activity, poverty, and eating habits. Food Nutr Bull. 2013; 34(4):388–401. Epub 2014/03/13. https://doi.org/10.1177/156482651303400404 PMID: 24605689.

66. Melkevik O, Torsheim T, Iannotti RJ, Wold BJIJoBN, Activity P. Is spending time in screen-based sedentary behaviors associated with less physical activity: a cross national investigation. 2010; 7(1):46.

67. Hare-Bruun H, Nielsen BM, Kristensen PL, Moller NC, Togo P, Heitmann BL. Television viewing, food preferences, and food habits among children: a prospective epidemiological study. BMC Public Health. 2011; 11:311. Epub 2011/05/17. https://doi.org/10.1186/1471-2458-11-311 PubMed Central PMCID: PMCPMC3112126. PMID: 21569476

68. Cleland V, Schmidt M, Dwyer T, Venn A. Television viewing and abdominal obesity in young adults: is the association mediated by food and beverage consumption during viewing time or reduced leisure-time physical activity? Am J Clin Nutr. 2008; 87(5):1148–55. WOS:000255880500008. https://doi.org/10.1093/ajcn/87.5.1148 PMID: 18469233

69. Shakir RN, Coates AM, Olds T, Rowlands A, Tsiros MDJOr, practice c. Not all sedentary behaviour is equal: Children's adiposity and sedentary behaviour volumes, patterns and types. 2018.

70. Ridgway CL, Ong KK, Tammelin T, Sharp SJ, Ekelund U, Jarvelin MR. Birth size, infant weight gain, and motor development influence adult physical performance. Med Sci Sports Exerc. 2009; 41(6):1212–21. Epub 2009/05/23. https://doi.org/10.1249/MSS.0b013e31819794ab PMID: 19461546.

71. Dodds R, Denison HJ, Ntani G, Cooper R, Cooper C, Sayer AA, et al. Birth weight and muscle strength: a systematic review and meta-analysis. The journal of nutrition, health & aging. 2012; 16(7):609–15. Epub 2012/07/28. PMID: 22836701.

72. Rogers M, Fay TB, Whitfield MF, Tomlinson J, Grunau RE. Aerobic capacity, strength, flexibility, and activity level in unimpaired extremely low birth weight (<or = 800 g) survivors at 17 years of age compared with term-born control subjects. Pediatrics. 2005; 116(1):e58–65. Epub 2005/07/06. https://doi.org/10.1542/peds.2004-1603 PMID: 15997047.

73. Boreham CA, Murray L, Dedman D, Davey Smith G, Savage JM, Strain JJ. Birthweight and aerobic fitness in adolescents: the Northern Ireland Young Hearts Project. Public Health. 2001; 115(6):373–9. Epub 2002/01/10. https://doi.org/10.1038/sj/ph/1900800 PMID: 11781846.

74. Lawlor DA, Cooper AR, Bain C, Davey Smith G, Irwin A, Riddoch C, et al. Associations of birth size and duration of breast feeding with cardiorespiratory fitness in childhood: findings from the Avon Longitudinal Study of Parents and Children (ALSPAC). Eur J Epidemiol. 2008; 23(6):411–22. Epub 2008/05/13. https://doi.org/10.1007/s10654-008-9259-x PMID: 18470625.

75. Ortega FB, Labayen I, Ruiz JR, Martin-Matillas M, Vicente-Rodriguez G, Redondo C, et al. Are muscular and cardiovascular fitness partially programmed at birth? Role of body composition. J Pediatr. 2009; 154(1):61–6 e1. Epub 2008/09/12. https://doi.org/10.1016/j.jpeds.2008.07.041 PMID: 18783796.

76. Inskip HM, Godfrey KM, Martin HJ, Simmonds SJ, Cooper C, Sayer AA, et al. Size at birth and its relation to muscle strength in young adult women. Journal of internal medicine. 2007; 262(3):368–74. Epub 2007/08/19. https://doi.org/10.1111/j.1365-2796.2007.01812.x PMID: 17697158; PubMed Central PMCID: PMCPMC2062503.

77. Cafiero G, Fintini D, Brufani C, Fiori R, Giordano U, Turchetta A, et al. Cardiovascular fitness is impaired in children born small for gestational age. Acta Paediatr. 2014; 103(5):e219–21. Epub 2014/01/28. https://doi.org/10.1111/apa.12571 PMID: 24460743.

78. Brutsaert TD, Tamvada KH, Kiyamu M, White DD, Gage TB. Low ponderal index is associated with decreased muscle strength and fatigue resistance in college-aged women. Early Hum Dev. 2011; 87(10):663–9. Epub 2011/06/07. https://doi.org/10.1016/j.earlhumdev.2011.05.006 PMID: 21641734; PubMed Central PMCID: PMCPMC3179787.

79. Andersen LG, Angquist L, Gamborg M, Byberg L, Bengtsson C, Canoy D, et al. Birth weight in relation to leisure time physical activity in adolescence and adulthood: meta-analysis of results from 13 nordic cohorts. PLoS One. 2009; 4(12):e8192. Epub 2009/12/18. https://doi.org/10.1371/journal.pone.0008192 PMID: 20016780; PubMed Central PMCID: PMCPMC2790716.

80. van Deutekom AW, Chinapaw MJ, Vrijkotte TG, Gemke RJ. The association of birth weight and infant growth with physical fitness at 8–9 years of age—the ABCD study. Int J Obes (Lond). 2015; 39(4):593–600. Epub 2014/12/04. https://doi.org/10.1038/ijo.2014.204 PMID: 25468828.

81. Bruch H. Psychological Aspects of Overeating and Obesity. Psychosomatics. 1964; 5:269–74. Epub 1964/09/01. PMID: 14235740.

82. Wardle J, Marsland L, Sheikh Y, Quinn M, Fedoroff I, Ogden J. Eating style and eating behaviour in adolescents. Appetite. 1992; 18(3):167–83. Epub 1992/06/01. PMID: 1510461.

83. Lluch A, Herbeth B, Mejean L, Siest G. Dietary intakes, eating style and overweight in the Stanislas Family Study. Int J Obes Relat Metab Disord. 2000; 24(11):1493–9. Epub 2000/01/11. PMID: 11126347.

84. Croker H, Cooke L, Wardle J. Appetitive behaviours of children attending obesity treatment. Appetite. 2011; 57(2):525–9. Epub 2011/06/11. https://doi.org/10.1016/j.appet.2011.05.320 PMID: 21658420.

85. Santos JL, Ho-Urriola JA, Gonzalez A, Smalley SV, Dominguez-Vasquez P, Cataldo R, et al. Association between eating behavior scores and obesity in Chilean children. Nutrition journal. 2011; 10:108. Epub 2011/10/12. https://doi.org/10.1186/1475-2891-10-108 PMID: 21985269; PubMed Central PMCID: PMCPMC3213088.

86. Webber L, Hill C, Saxton J, Van Jaarsveld CH, Wardle J. Eating behaviour and weight in children. Int J Obes (Lond). 2009; 33(1):21–8. Epub 2008/11/13. https://doi.org/10.1038/ijo.2008.219 PMID: 19002146; PubMed Central PMCID: PMCPMC2817450.

87. Eloranta AM, Lindi V, Schwab U, Tompuri T, Kiiskinen S, Lakka HM, et al. Dietary factors associated with overweight and body adiposity in Finnish children aged 6–8 years: the PANIC Study. Int J Obes (Lond). 2012; 36(7):950–5. Epub 2012/06/06. https://doi.org/10.1038/ijo.2012.89 PMID: 22665136.

88. Mericq V, Medina P, Kakarieka E, Marquez L, Johnson MC, Iniguez G. Differences in expression and activity of 11beta-hydroxysteroid dehydrogenase type 1 and 2 in human placentas of term pregnancies according to birth weight and gender. Eur J Endocrinol. 2009; 161(3):419–25. Epub 2009/06/23. https://doi.org/10.1530/EJE-09-0308 PMID: 19542242.

89. van Strien T, Roelofs K, de Weerth C. Cortisol reactivity and distress-induced emotional eating. Psychoneuroendocrinology. 2013; 38(5):677–84. Epub 2012/09/25. https://doi.org/10.1016/j.psyneuen.2012.08.008 PMID: 22999262.

90. van Strien T, Herman CP, Verheijden MW. Eating style, overeating and weight gain. A prospective 2-year follow-up study in a representative Dutch sample. Appetite. 2012; 59(3):782–9. Epub 2012/08/25. https://doi.org/10.1016/j.appet.2012.08.009 PMID: 22918175.

91. Palmiter RD. Is dopamine a physiologically relevant mediator of feeding behavior? Trends in neurosciences. 2007; 30(8):375–81. Epub 2007/07/03. https://doi.org/10.1016/j.tins.2007.06.004 PMID: 17604133.

92. Narayanan NS, Guarnieri DJ, DiLeone RJ. Metabolic hormones, dopamine circuits, and feeding. Front Neuroendocrinol. 2010; 31(1):104–12. Epub 2009/10/20. https://doi.org/10.1016/j.yfrne.2009.10.004 PMID: 19836414; PubMed Central PMCID: PMCPMC2813908.

93. Eisenstein SA, Bischoff AN, Gredysa DM, Antenor-Dorsey JA, Koller JM, Al-Lozi A, et al. Emotional Eating Phenotype is Associated with Central Dopamine D2 Receptor Binding Independent of Body Mass Index. Scientific reports. 2015; 5:11283. Epub 2015/06/13. https://doi.org/10.1038/srep11283 PMID: 26066863; PubMed Central PMCID: PMCPMC4464302.

94. Volkow ND, Wang GJ, Maynard L, Jayne M, Fowler JS, Zhu W, et al. Brain dopamine is associated with eating behaviors in humans. Int J Eat Disord. 2003; 33(2):136–42. Epub 2003/03/05. https://doi.org/10.1002/eat.10118 PMID: 12616579.

95. Noschang C, Portella A, Cardoso S, Bittencourt V, Dalmaz C, Goldani M, et al. Neonatal Overfeeding Induced by Reducing the Litter Size Leads to an Obese Phenotype and Increases Preference for Sweet Food in Adult Male Rats British Journal of Medicine & Medical Research. 2014; 4(4). Epub 968.

96. Portella AK, Silveira PP, Laureano DP, Cardoso S, Bittencourt V, Noschang C, et al. Litter size reduction alters insulin signaling in the ventral tegmental area and influences dopamine-related behaviors in adult rats. Behav Brain Res. 2015; 278:66–73. Epub 2014/09/30. https://doi.org/10.1016/j.bbr.2014.09.033 PMID: 25264577.

97. Laureano D, Dalle Molle R, Alves M, Luft C, Desai M, Ross M, et al. Intrauterine growth restriction modifies the hedonic response to sweet taste in newborn pups–Role of the accumbal μ-opioid receptors. Neuroscience. 2016; 322:500–8. https://doi.org/10.1016/j.neuroscience.2016.02.033 PMID: 26926962

98. Escobar RS, O'Donnell KA, Colalillo S, Pawlby S, Steiner M, Meaney MJ, et al. Better quality of mother-child interaction at 4 years of age decreases emotional overeating in IUGR girls. Appetite. 2014; 81:337–42. Epub 2014/07/12. https://doi.org/10.1016/j.appet.2014.06.107 PMID: 25014742.

99. Lussana F, Painter RC, Ocke MC, Buller HR, Bossuyt PM, Roseboom TJ. Prenatal exposure to the Dutch famine is associated with a preference for fatty foods and a more atherogenic lipid profile. Am J Clin Nutr. 2008; 88(6):1648–52. https://doi.org/10.3945/ajcn.2008.26140 PMID: 19064527.

100. Bellinger L, Langley-Evans SC. Fetal programming of appetite by exposure to a maternal low-protein diet in the rat. Clin Sci (Lond). 2005; 109(4):413–20. Epub 2005/07/05. https://doi.org/10.1042/CS20050127 PMID: 15992360.

101. Vickers MH, Breier BH, Cutfield WS, Hofman PL, Gluckman PD. Fetal origins of hyperphagia, obesity, and hypertension and postnatal amplification by hypercaloric nutrition. Am J Physiol Endocrinol Metab. 2000; 279(1):E83–7. Epub 2000/07/14. https://doi.org/10.1152/ajpendo.2000.279.1.E83 PMID: 10893326.

102. Bellinger L, Sculley DV, Langley-Evans SC. Exposure to undernutrition in fetal life determines fat distribution, locomotor activity and food intake in ageing rats. Int J Obes (Lond). 2006; 30(5):729–38. Epub 2006/01/13. https://doi.org/10.1038/sj.ijo.0803205 PMID: 16404403; PubMed Central PMCID: PMCPMC1865484.

103. Plagemann A, Harder T, Brunn M, Harder A, Roepke K, Wittrock-Staar M, et al. Hypothalamic proopiomelanocortin promoter methylation becomes altered by early overfeeding: an epigenetic model of obesity and the metabolic syndrome. J Physiol. 2009; 587(Pt 20):4963–76. Epub 2009/09/03. https://doi.org/10.1113/jphysiol.2009.176156 PMID: 19723777; PubMed Central PMCID: PMCPMC2770159.

104. van Deutekom AW, Chinapaw MJ, Jansma EP, Vrijkotte TG, Gemke RJ. The Association of Birth Weight and Infant Growth with Energy Balance-Related Behavior—A Systematic Review and Best-Evidence Synthesis of Human Studies. PLoS One. 2017; 12(1):e0168186. Epub 2017/01/13. https://doi.org/10.1371/journal.pone.0168186 PMID: 28081150; PubMed Central PMCID: PMCPMC5232347.

105. Perala MM, Mannisto S, Kaartinen NE, Kajantie E, Osmond C, Barker DJ, et al. Body size at birth is associated with food and nutrient intake in adulthood. PLoS One. 2012; 7(9):e46139. Epub 2012/10/11. https://doi.org/10.1371/journal.pone.0046139 PMID: 23049962; PubMed Central PMCID: PMCPMC3458835.

106. Kaseva N, Wehkalampi K, Hemio K, Hovi P, Jarvenpaa AL, Andersson S, et al. Diet and nutrient intake in young adults born preterm at very low birth weight. J Pediatr. 2013; 163(1):43–8. Epub 2013/02/09. https://doi.org/10.1016/j.jpeds.2012.12.076 PMID: 23391045.

107. Zornoza-Moreno M, Fuentes-Hernandez S, Prieto-Sanchez MT, Blanco JE, Pagan A, Rol MA, et al. Influence of gestational diabetes on circadian rhythms of children and their association with fetal adiposity. Diabetes/metabolism research and reviews. 2013; 29(6):483–91. Epub 2013/04/10. https://doi.org/10.1002/dmrr.2417 PMID: 23568539.

108. McDonald L, Wardle J, Llewellyn CH, Fisher A. Nighttime sleep duration and hedonic eating in childhood. Int J Obes (Lond). 2015; 39(10):1463–6. Epub 2015/07/21. https://doi.org/10.1038/ijo.2015.132 PMID: 26189601; PubMed Central PMCID: PMCPMC4597336.

109. Sokolovic N, Kuriyan R, Kurpad AV, Thomas T. Sleep and birthweight predict visceral adiposity in overweight/obese children. Pediatric obesity. 2013; 8(3):e41–4. Epub 2013/03/21. https://doi.org/10.1111/j.2047-6310.2012.00142.x PMID: 23512928.

110. St-Onge MP. The role of sleep duration in the regulation of energy balance: effects on energy intakes and expenditure. J Clin Sleep Med. 2013; 9(1):73–80. Epub 2013/01/16. https://doi.org/10.5664/jcsm.2348 PMID: 23319909; PubMed Central PMCID: PMCPMC3525993.

111. Hancox RJ, Landhuis CE. Association between sleep duration and haemoglobin A1c in young adults. J Epidemiol Community Health. 2012; 66(10):957–61. Epub 2011/11/10. https://doi.org/10.1136/jech-2011-200217 PMID: 22068028.

112. Tehranifar P, Liao Y, Flom JD, Terry MB. Validity of self-reported birth weight by adult women: sociodemographic influences and implications for life-course studies. Am J Epidemiol. 2009; 170(7):910–7. Epub 2009/09/15. https://doi.org/10.1093/aje/kwp205 PMID: 19748903; PubMed Central PMCID: PMCPMC2765356.

113. Ekström S, Kull I, Nilsson S, Bergström A. Web-based self-reported height, weight, and body mass index among Swedish adolescents: a validation study. Journal of medical Internet research. 2015; 17 (3).

114. Kakinami L, Henderson M, Chiolero A, Cole TJ, Paradis G. Identifying the best body mass index metric to assess adiposity change in children. Arch Dis Child. 2014; 99(11):1020–4. Epub 2014/05/21. https://doi.org/10.1136/archdischild-2013-305163 PMID: 24842797; PubMed Central PMCID: PMCPMC4215345.

115. Wicklow BA, Becker A, Chateau D, Palmer K, Kozyrskij A, Sellers EA. Comparison of anthropometric measurements in children to predict metabolic syndrome in adolescence: analysis of prospective cohort data. Int J Obes (Lond). 2015; 39(7):1070–8. Epub 2015/04/15. https://doi.org/10.1038/ijo.2015.55 PMID: 25869598.