

ORIGINAL RESEARCH **OPEN ACCESS**

Longer Breastfeeding Is Associated With Healthier Body Mass Index Trajectories and Lower Risk of Overweight and Obesity in Youth Aged 9–12 Years

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Received: 24 April 2025 | **Revised:** 29 December 2025 | **Accepted:** 1 January 2026

Keywords: adolescence | breastfeeding | longitudinal | obesity | puberty | weight gain

ABSTRACT

Background: The association between breastfeeding and adolescent obesity remains unclear because most previous studies included youth with obesity. We explored these associations from ages 9 to 12 amongst initially healthy weight youth.

Methods: The analytic sample included 4161 youth (10 586 observations across three assessments; all healthy weight at baseline; 50.7% female; 52% breastfed more than 6 months) from the Adolescent Brain Cognitive Development (ABCD) Study. Linear mixed-effects models examined breastfeeding \times age \times sex and breastfeeding \times puberty \times sex interactions on BMI trajectories (kg/m^2). Logistic regression estimated the risk of unhealthy weight (BMI \geq 85th percentile) by ages 11–12. All analyses were stratified by sex.

Results: Three-way interactions were not significant. Significant breastfeeding \times age interactions ($\beta = -0.005$, $p < 0.001$) indicated that breastfed youth exhibited lower BMI trajectories, particularly when breastfed for more than 6 months ($\beta = -0.006$, $p < 0.001$). Significant breastfeeding \times puberty interactions showed lower BMI trajectories across pubertal stages amongst breastfed youth ($\beta = -0.06$, $p = 0.017$), observed only in boys and especially in those breastfed beyond 6 months ($\beta = -0.11$, $p = 0.005$). Breastfeeding was associated with a reduced unhealthy weight risk at ages 11–12 (RR = 0.78, $p = 0.002$), exclusively in boys and amongst those breastfed more than 6 months (RR = 0.52, $p < 0.001$). No associations were found in girls.

Conclusion: Amongst initially healthy weight youth, breastfeeding, especially beyond 6 months, was associated with healthier BMI trajectories and lower unhealthy weight risk in boys. Although these sex-specific patterns warrant further research, our findings suggest that the associations between breastfeeding and body weight development extend into adolescence.

1 | Introduction

Recent systematic review [1] and meta-analysis [2] indicate that breastfeeding is considered a protective factor against excessive weight gain and obesity. Whilst these studies suggest that these positive associations may extend into childhood [3], it remains unclear whether breastfeeding benefits extend into adolescence,

a critical period for weight-gain risk [4]. Adolescence, a period that spans from ages 10–19 years [5], is marked by puberty-induced hormonal changes that increase food intake and weight gain, which are necessary for physical growth and reproduction [4]. Whilst weight gain during adolescence is expected, the current obesogenic environment may exacerbate weight gain for some youth [6]. Some research has postulated that

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breastfeeding, correlated with enhanced satiety responsiveness [7] and improved regulation of food intake [8], may prevent excessive weight gain and obesity during this period. However, no studies have explicitly examined this in adolescents who did not yet have obesity. Given the established relationship between obesity and breastfeeding, research on these associations could help clarify whether the benefits of breastfeeding extend beyond infancy and early childhood, thereby strengthening public health messages.

The association between breastfeeding and weight gain and obesity during early childhood has been documented in a recent meta-analysis [2]. Although the mechanism is poorly understood, breast milk is thought to influence early metabolic programming, enhancing satiety responsiveness and reducing caloric intake [7]. In contrast, formula milk, much richer in protein content and sometimes in added sugars, has been associated with rapid growth (see systematic review and meta-analysis) [9] and obesity [10, 11]. In addition, breastfeeding is self-regulated by the infant, whereas formula feeding is controlled by the caregiver. Bottle-feeding has been associated with overfeeding and weight gain [8]. This may ultimately contribute to reducing the child's reliance on internal hunger and satiety signals, increasing the risk of future overeating and obesity [12].

Despite systematic review [1] and meta-analysis [2] showing that breastfeeding is associated with healthier weight trajectories and lower incidence of obesity in children, evidence in adolescence remains limited. A significant flaw of adolescent studies is that they all included youth who developed obesity before this period [13–19]. Therefore, this prevents confirming whether the associations between breastfeeding and healthy weight trajectories remain active during this critical period. Also, these studies have been limited by small sample sizes [14], or conducted on samples that lack diversity (see Table 1 for a summary of seminal studies) [13, 15–18]. As worldwide breastfeeding practices are declining [20] and global childhood obesity rates are increasing (see review [21]), it is critical to determine whether breastfeeding is associated with healthier weight trajectories during the transition from childhood to early adolescence, which can be important for public health messaging.

This study builds on these gaps in the literature by examining the longitudinal associations over a 2-year period between breastfeeding and weight gain in a sample of youth who, at the beginning of the study and according to the CDC growth curves [22], were considered of a healthy weight. By the year 2 follow-up, 10% transitioned to overweight and 0.2% to obesity. Specifically, we investigated whether breastfeeding correlated with BMI trajectories from 9 to 12 years and with the progression to overweight and obesity (BMI percentile ≥ 85 th) at ages 11–12. We leveraged data from three timepoints from the Adolescent Brain Cognitive Development (ABCD) Study, a large and diverse cohort of youth. Importantly, our study also aimed to disentangle the associations of age (i.e., ageing over time) and puberty (i.e., biological maturation) on the relationship between breastfeeding and weight gain. Additionally, as boys and girls undergo puberty at different times [23], we examined all these relationships first in the whole sample and separately by sex. We hypothesised that breastfeeding (and longer durations) would be associated with lower BMI trajectories and decreased risk

of transitioning to overweight and obesity during early adolescence and pubertal development.

2 | Materials and Methods

2.1 | Study Design

The ABCD Study is a 10-year, 21-site research project that began between 2016 and 2018, with participants enrolled at either 9 or 10 years old. Recruitment was designed to reflect the diverse characteristics of the US population as best as possible. The ABCD Study was responsible for obtaining caregiver consent and youth assent. The overall protocol received approval from the centralised Institutional Review Board at the University of California, San Diego. This manuscript utilises data from the 5.1 release (<https://doi.org/10.15154/z563-zd24>) and focuses on baseline and follow-up visits during year 1 (2018–2020) and year 2 (2020–2022). Additionally, this manuscript used data from the year 3 follow-up (2022–2024) for cross-referencing breastfeeding reports only (more details in this section). Whilst the ABCD Study had minimal exclusions, the current analysis applied additional exclusions (e.g., prenatal exposure to drugs, including but not limited to alcohol and tobacco, extreme prematurity, very low birth weight, etc.). Participants with post-2020 pandemic lockdown or remote visits were excluded to minimise bias from COVID-19-related weight gain or measurement errors from in-home self-assessments. Details regarding exclusion, including a participant's flowchart, can be found in the Supporting Information [Methods S1–S2](#). Since some data were gathered from families with multiple participants, we randomly selected one representative per family, prioritising the participant with the most data across the three visits.

2.2 | Demographics and Physical Characteristics

At baseline, caregivers reported the youth's age, birth weight, race, ethnicity, sex, caregiver education, total annual household income, prenatal substance exposure, perinatal issues, mode of delivery, and prematurity. Age was collected in months. Birth weight was reported in kilograms. Race was obtained through a 19-item response system and collapsed into six category groups for descriptive purposes only: American Indian/Native American, Native Hawaiian/Pacific Islander, Asian, Black, Mixed, Other, and White. Ethnicity was assessed with a binary response (Hispanic/Latinx, non-Hispanic/Latinx). Caregiver education was reported on a 21-item scale for both caregivers in the household and categorised into five groups: less than high school (< 13 years), high school graduate (13–14 years), some college (15–17 years), bachelor's degree (18 years), and postgraduate degree (19–21 years). Total annual household income was classified into three categories: less than \$50 000, \$50 000–\$99 999, and more than \$100 000. Due to omissions and potential inaccuracies in income reporting, the maximum level of education achieved by either caregiver within the household was used as a proxy for socioeconomic status in our analyses. Prenatal substance exposure (e.g., alcohol, tobacco, marijuana, opiates, opioids, cocaine, and/or crack) was retrospectively assessed before and after pregnancy knowledge through a binary response (Yes/No) questionnaire at baseline by the attending caregiver.

TABLE 1 | Summary of studies exploring breastfeeding and BMI associations during adolescence.

Study	Age range	N	Follow up duration	Outcome	Main predictor	Covariates	Findings
Cheng et al., 2018	0–16	7367	16 years	BMIz	Feeding modality (exclusive breastfed, mixed, exclusive formula)	Smoking, household income, maternal education, maternal age, maternal birthplace, parity, gestational age, and weight-for-age z-score at birth	No relationship found
Garden et al., 2012	0–11.5	370	11.5 years	BMI (raw)	Breastfeeding duration (0–3, 3–6, > 6 months)	Dietary intervention group, parental obesity, ethnicity, smoking, father's education	No relationship found
Sherwood et al., 2019	0–18	602	18 years	BMI (raw)	Exclusive breastfeeding duration (weeks) and total breastfeeding duration (weeks)	Sex, maternal socioeconomic status, smoking, gestational age	Total breastfeeding duration negatively associated with early transient overweight
Wu et al., 2020	0–18	5266	18 years	BMI (raw)	Exclusive breastfeeding duration (months)	Gestational age, maternal pre-pregnancy BMI, education, smoking status, family income	In genetically susceptible children, exclusive breastfeeding for 5 months was related to lower BMI at 18y
Liu et al., 2022	6–16	10753	Cross-sectional	BMI (raw) and weight class status	Breastfeeding duration (months)	Age, sex, ethnicity, parity, mode of delivery, birth gestational week, birthweight, birth length	Negative association between breastfeeding duration and BMI, especially in boys breastfed > 12 months
Li et al., 2012	2–12	1739	10 years	Weight class status	Breastfeeding duration (weeks)	Sex, race, birth order, gestational age, birthweight, maternal pre-pregnancy BMI, gestational weight gain, smoking and alcohol use, maternal age at birth, mother's education, family net income	≥ 4 months (16 weeks) of breastfeeding was related to lower risk of early (before 2 years) and late (after 8 years) overweight onset

Caregivers also retrospectively reported on non-exclusionary pregnancy complications, non-hospitalised birth issues, delivery mode (Vaginal/Caesarean), and prematurity (Term/Preterm). Information on youth- and parent-reported perceptions of the youth's pubertal status was collected using the Pubertal Developmental Scale (PDS; continuous) [24]. PDS scores (ranges 1–5) were used to classify children as pre-pubertal (1), early-pubertal (2), mid-pubertal (3), late-pubertal (4), and post-pubertal (5). Since puberty was central to the current paper, and because only five individuals qualified as post-pubertal (after applying other exclusion criteria), these were discarded as there were not enough youths in this bin to conduct the analyses. Details regarding pubertal assessment can be found in the Supporting Information Methods S3.

2.3 | Breastfeeding Duration

At baseline, caregivers retrospectively reported their child's breastfeeding duration in months using an open-ended question ("For how many months was your child breastfed?"). At the 3-year follow-up, breastfeeding duration was retrospectively reported again but using an 8-point Likert scale (0=no breastfeeding, only formula; 1=several days; 2=1–3 months; 3=4–6 months; 4=7–9 months; 5=10–12 months; 6=13–18 months; 7=19–24 months; 8=more than 24 months). To harmonise these data across time points, baseline responses in months were converted to the Likert scale used at follow-up. Participants with large discrepancies in reported duration, such as those who reported no breastfeeding at baseline but a positive duration at year 3, or vice versa, were excluded. Amongst participants who reported some breastfeeding at both time points, if there was a discrepancy greater than one scale point, these data were excluded. For instance, a report of 4–6 months (response 3) at baseline and 1–3 months (response 2) at follow-up was retained, whereas a report of 4–6 months and 10–12 months (response 5) resulted in exclusion. Breastfeeding was categorised into two groups: no breastfeeding (0 months) and any breastfeeding. Consistent with guideline-based cutoffs [25], breastfeeding durations were collapsed into three categories: no breastfeeding (0 months, only formula), breastfeeding 6 months or less, and breastfeeding for more than 6 months.

2.4 | Anthropometric Assessment

Height and weight were assessed by a trained researcher and converted to BMI (kg/m^2) at baseline (ages 9–10) and follow-up visits in years 1 (ages 10–11) and 2 (ages 11–12); details can be found in the Supporting Information Methods S4. According to the CDC's growth charts, the youth's weight was classified into the following groups: underweight (BMI \leq 5th percentile), healthy weight (BMI < 85th percentile), overweight (BMI \geq 85th percentile), and obesity (BMI \geq 95th percentile) [22]. As this study examined whether breastfeeding was associated with reduced excessive weight gain and a lower risk of transitioning to overweight and obesity, youth with overweight or obesity (i.e., BMI \geq 85th percentile) at baseline were excluded [22]. Underweight youth (BMI \leq 5th percentile and weight < 15 kg) or those who have lost more than 20 kg in a year were also excluded due to issues with restrictive feeding and/or medical conditions

that prevent weight gain. This study only considered youth who completed on-site or hybrid visits that included in-person physical height and weight assessments before the COVID-19 lockdown announcement on March 19, 2020.

3 | Statistical Analysis

All statistical analyses were performed using R (version 4.3.1) and R Studio (version 2025.5.0.496). Before any statistical analysis, all continuous variables were inspected for severe skewness (absolute skewness > 2) or high kurtosis (absolute kurtosis > 7) [26] with the *e1071* R package (version 1.7–16). Covariates were selected based on data collected by the ABCD Study and prior literature describing associations between these and child weight (see Table 1). Continuous covariates, including age (in months), birth weight (in kg), and puberty (PDS score), were mean-centred to reduce multicollinearity and improve model interpretability and convergence. Categorical covariates, such as sex (boy/girl) and education (less than high school, high school/generalised education degree, some college, bachelor, postgrad), were sum-to-zero coded, so that the model intercepts represented the overall mean, irrespective of group, rather than the mean of the reference group as in dummy-coding. Both mean-centering and sum-to-zero coding were performed on the entire sample and then separately for boys and girls. Breastfeeding status was categorised in binary terms based on duration as "formula-fed" (0 months) and "breastfed" (1 month or more). Breastfeeding duration was categorised into three groups: no breastfeeding (0 months, formula-fed), breastfeeding for 6 months or less, and breastfeeding for more than 6 months. Breastfeeding duration was Helmert-coded (see next section for details). Multicollinearity was assessed by examining the correlation between covariates (absolute pairwise Pearson's correlation > 0.8) and by inspecting the variance inflation factor (VIF > 5). Continuous demographic and clinical variables were compared at baseline amongst breastfeeding status groups (2 groups) using *t*-tests. *F*-tests were used to compare breastfeeding duration groups (3 groups). χ_2 tests were used to compare categorical variables amongst groups. Statistical significance was set at $p < 0.05$ for all tests.

3.1 | Is Breastfeeding Associated With Reduced Weight Gain From 9 to 12 Years of Age?

Analyses examining BMI continuously used raw BMI scores rather than standardised BMI scores (e.g., CDC's BMI percentiles), as is recommended with longitudinal study designs when more precise measures of adiposity are not available [27–30]. We first examined the relationship between BMI and breastfeeding status (BF status) using linear mixed-effects (LME) models from ages 9 to 12. Analyses for the whole sample included a three-way interaction amongst BF status \times age \times sex. Due to potential influences on BMI, all models controlled for the fixed effects of puberty (see review [31]), education [32], and birth weight [33]. Subject (ID) and site influences were treated as crossed random effects. The sex-stratified analyses did not consider sex as a covariate. We report unstandardized beta coefficients (β) and confidence intervals (CI) at 95%. The LME model's syntax can be found below:

$$\begin{aligned} \text{BMI} &\sim \text{BF status} \times \text{age} \times \text{sex} + \text{puberty} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \\ \text{BMI}_{\text{boys}} &\sim \text{BF status} \times \text{age} + \text{puberty} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \\ \text{BMI}_{\text{girls}} &\sim \text{BF status} \times \text{age} + \text{puberty} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \end{aligned}$$

3.2 | Is Breastfeeding Duration Associated With Reduced Weight Gain From 9 to 12 Years of Age?

LME models examining BMI trajectories from 9 to 12 years in relation to breastfeeding duration (BF duration) included two contrasts: Contrast 1 examined the difference in BMI over time between youth who were not breastfed and youth who were breastfed for 6 months or less, ignoring youth who were breastfed for more than 6 months (Contrast 1: $-1, 1, 0$). Contrast 2 explored differences in BMI trajectories amongst individuals who were breastfed for more than 6 months compared to those who were not breastfed or who were breastfed 6 months or less (Contrast 2: $-0.5, -0.5, 1$). These associations were tested in a three-way interaction with sex (BF duration \times age \times sex). Sex-stratified models followed this initial model. All models were controlled for puberty, education, and birth weight. Crossed-random effects of the subject (ID) and site were also included. The model's syntax can be found below:

$$\begin{aligned} \text{BMI} &\sim \text{BF duration} \times \text{age} \times \text{sex} + \text{puberty} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \\ \text{BMI}_{\text{boys}} &\sim \text{BF duration} \times \text{age} + \text{puberty} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \\ \text{BMI}_{\text{girls}} &\sim \text{BF duration} \times \text{age} + \text{puberty} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \end{aligned}$$

3.3 | Is Breastfeeding, and Breastfeeding Duration, Associated With Reduced Weight Gain Throughout Puberty?

Due to concerns about chronological age not being an accurate proxy of maturation during this period, we used the average of self- and parent-reported youth puberty assessments (PDS scores). This score replaced age as part of the three-way interaction (BF status \times puberty \times sex and BF duration \times puberty \times sex). Age was kept in the models as a confounder, along with education, birth weight, and the crossed-random effects of subject and site. As puberty differs by sex [23], we also conducted these analyses separately by boys and girls. A summary of the models' syntaxes can be found below.

3.3.1 | Breastfeeding Status and Puberty

$$\begin{aligned} \text{BMI} &\sim \text{BF status} \times \text{puberty} \times \text{sex} + \text{age} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \\ \text{BMI}_{\text{boys}} &\sim \text{BF status} \times \text{puberty} + \text{age} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \end{aligned}$$

$$\begin{aligned} \text{BMI}_{\text{girls}} &\sim \text{BF status} \times \text{puberty} + \text{age} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \end{aligned}$$

3.3.2 | Breastfeeding Duration and Puberty

$$\begin{aligned} \text{BMI} &\sim \text{BF duration} \times \text{puberty} \times \text{sex} + \text{age} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \\ \text{BMI}_{\text{boys}} &\sim \text{BF duration} \times \text{puberty} + \text{age} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \\ \text{BMI}_{\text{girls}} &\sim \text{BF duration} \times \text{puberty} + \text{age} + \text{education} \\ &+ \text{birth weight} + (1 \mid \text{ID}) + (1 \mid \text{site}) \end{aligned}$$

3.4 | Is Breastfeeding, and Breastfeeding Duration, Associated With a Lower Risk of Transitioning to Unhealthy Weight at Ages 11–12?

We quantified the extent to which breastfeeding (status and duration) was related to a lower risk of transitioning from a healthy weight at baseline (ages 9–10) to an unhealthy weight (BMI percentile ≥ 85 th) at the 2-year follow-up visit (ages 11–12). Thus, this cross-sectional analysis leveraged data from the 2-year follow-up visit. BMI group, the outcome variable, was classified as healthy (BMI < 85 th percentile) and unhealthy (BMI ≥ 85 th percentile) based on the CDC's BMI classification [22]. BF status (and BF duration in a separate model) was treated as the primary predictor. The analysis was adjusted for sex, age, puberty, education, and birth weight. Since healthy and unhealthy weight youth were not proportionately distributed across sites, a logistic linear regression was conducted instead of a logistic mixed-model regression. Due to concerns about group imbalances in the data at this visit (i.e., 2358 healthy weight vs. 286 unhealthy weight), we balanced the number of observations per group using an inverse class frequency weighting (weight = total healthy weight / total unhealthy weight). In other words, each individual with an unhealthy weight contributed eight times more to the model than a healthy weight individual to ensure balance. Weighting was done first across sexes and then separately by sex. We report the relative risk (RR) and the CI at 95% associated with breastfeeding (status and duration). We also report the accuracy of the model (i.e., area under the curve, AUC) in predicting participants with unhealthy weight.

3.4.1 | Breastfeeding Status and Unhealthy Weight

$$\begin{aligned} \text{Group BMI} &\sim \text{BF status} + \text{age} + \text{puberty} + \text{sex} + \text{education} \\ &+ \text{birth weight} \\ \text{Group BMI}_{\text{boys}} &\sim \text{BF status} + \text{age} + \text{puberty} + \text{education} \\ &+ \text{birth weight} \\ \text{Group BMI}_{\text{girls}} &\sim \text{BF status} + \text{age} + \text{puberty} + \text{education} \\ &+ \text{birth weight} \end{aligned}$$

3.4.2 | Breastfeeding Duration and Unhealthy Weight

$$\begin{aligned} \text{Group BMI} &\sim \text{BF duration} + \text{age} + \text{puberty} + \text{sex} + \text{education} \\ &+ \text{birth weight} \end{aligned}$$

$$\begin{aligned} \text{Group BMI}_{\text{boys}} &\sim \text{BF duration} + \text{age} + \text{puberty} + \text{education} \\ &+ \text{birth weight} \\ \text{Group BMI}_{\text{girls}} &\sim \text{BF duration} + \text{age} + \text{puberty} + \text{education} \\ &+ \text{birth weight} \end{aligned}$$

4 | Results

A total of 11 868 participants from the ABCD Study were initially considered. After applying our study-specific exclusions, the final sample included 4161 individuals at baseline, 3782 at year 1, and 2643 at year 2. Table 2 below shows the characteristics of the entire ABCD Study sample, as well as a comparison between those included and excluded from the present study. More details regarding participant exclusion are available in the Supporting Information [Methods S1](#). The characteristics of the final sample across all visits are presented in Table 3.

Regarding baseline (ages 9-10) comparisons between breastfed ($n=3559$) and formula-fed youth ($n=602$), both were equally distributed for age ($t=0.81$, $p=0.435$) and sex ($X^2=0.04$, $p=0.834$). Breastfed youth had a lower PDS score ($t=-7.95$, $p<0.001$), weighed more at birth ($t=5.94$, $p<0.001$), and had a lower raw BMI ($t=-2.25$, $p=0.022$) and BMI percentile ($t=-2.52$, $p=0.010$) compared to formula-fed youth. See Table 4 for details on the comparisons at baseline based on breastfeeding status. Since groups differed for mode of delivery ($X^2=12.78$, $p=0.002$), pregnancy complications ($X^2=36.99$, $p<0.001$), birth issues ($X^2=6.53$, $p=0.038$), and prematurity ($X^2=6.11$, $p=0.013$), supplementary LME models additionally controlling for these factors were conducted. Results are presented in the Supporting Information [Results S1-S3](#). Differences for race ($X^2=290.65$, $p<0.001$), income ($X^2=203.84$, $p<0.001$), and education ($X^2=368.52$, $p<0.001$) were also noted.

By year 1 follow-up (ages 10-11), the distribution of healthy weight, overweight, and obesity was statistically different between breastfed and formula-fed youth ($X^2=6.64$, $p=0.036$), indicating a greater proportion of formula-fed youth had transitioned to overweight (11.0%) and obesity (0.8%) compared to breastfed youth (7.9% overweight, 0.5% obesity, respectively, see Table [S1](#)). By year 2 follow-up (ages 11-12), statistically significant differences were also found by weight status on breastfeeding ($X^2=8.60$, $p=0.014$). More youth from the formula-fed group transitioned to the overweight (14.2%) and obesity (0.8%) categories compared to those who were breastfed (9.3% overweight, 0.7% obesity, respectively, see Table [S2](#)). More details regarding comparisons across breastfeeding duration levels can be found in the Tables [S3-S5](#).

4.1 | Is Breastfeeding Associated With Reduced Weight Gain From 9 to 12 Years of Age?

The three-way interaction between breastfeeding status, age, and sex was not significant ($\beta=0.001$, 95% CI= -0.002 , 0.003 , $p=0.591$). However, the two-way interaction (breastfeeding status \times age) was found significant ($\beta=-0.005$, 95% CI= -0.007 , -0.002 , $p<0.001$), indicating that, irrespective of sex, youth who

were breastfed had a lower increase in BMI from 9 to 12 years of age compared to formula-fed youth. The sex-stratified analysis showed that breastfed boys ($\beta=-0.005$, 95% CI= -0.009 , -0.002 , $p=0.005$) and girls ($\beta=-0.004$, 95% CI= -0.008 , -0.0002 , $p=0.038$) exhibited statistically significant lower BMI increases than their formula-fed counterparts. See Figure 1 (panels A-C) for a graphical representation of these associations.

4.2 | Is Breastfeeding Duration Associated With Lower Weight Gain From 9 to 12 Years of Age?

No significant three-way interactions (breastfeeding status \times age \times sex) were found for contrast one (formula-fed vs. breastfed youth 6 months or less; $\beta=0.001$, 95% CI= -0.003 , 0.003 , $p=0.784$) nor contrast two (breastfed youth more than 6 months vs. formula-fed and breastfed youth 6 months or less; $\beta=-0.003$, 95% CI= -0.002 , 0.003 , $p=0.486$). No significant two-way interaction (breastfeeding status \times age) was found for contrast one ($\beta=-0.003$, 95% CI= -0.005 , 0.001 , $p=0.055$). However, a significant two-way interaction was found for contrast two ($\beta=-0.006$, 95% CI= -0.008 , -0.003 , $p<0.001$). In other words, youth who were breastfed for more than 6 months showed a decreased BMI trajectory from ages 9 to 12 compared to formula-fed youth and those who were breastfed for 6 months or less. The sex-stratified analysis confirmed that this two-way interaction was statistically significant in boys ($\beta=-0.007$, 95% CI= -0.010 , -0.003 , $p<0.001$) and girls ($\beta=-0.005$, 95% CI= -0.009 , -0.001 , $p=0.009$). A visual illustration of these relationships is available in Figure 1 (panels D-F).

4.3 | Is Breastfeeding Associated With Lower Weight Gain During Puberty?

The three-way interaction (breastfeeding status \times puberty \times sex) was not found significant ($\beta=0.04$, 95% CI= -0.009 , 0.089 , $p=0.109$). The two-way interaction (breastfeeding status \times puberty) was found to be statistically significant ($\beta=-0.005$, 95% CI= -0.110 , -0.012 , $p=0.017$). Simply, youth who were breastfed exhibited a lower BMI trajectory across pubertal stages (PDS scores). The sex-stratified analyses, however, demonstrated that this interaction was statistically significant in boys ($\beta=-0.10$, 95% CI= -0.18 , -0.02 , $p=0.013$) but not in girls ($\beta=-0.022$, 95% CI= -0.08 , 0.04 , $p=0.444$). This indicates that, as boys advance in puberty, the BMI slope of those who were breastfed was lower than that of those who were formula-fed. See Figure 2 (panels A-C) for details.

4.4 | Is Breastfeeding Duration Associated With Lower Weight Gain During Puberty?

No significant three-way interactions (breastfeeding duration \times puberty \times sex) were found for any of the two contrasts (contrast one: $\beta=0.035$, 95% CI= -0.019 , 0.089 , $p=0.207$; contrast two: $\beta=0.037$, 95% CI= -0.012 , 0.086 , $p=0.140$). A two-way interaction (breastfeeding status \times puberty) was found significant for contrast two only ($\beta=-0.08$, 95% CI= -0.13 , -0.03 , $p=0.002$). That is, compared to formula-fed youth and youth

TABLE 2 | Demographic and other variables of interest of the whole sample and baseline comparisons between those included and excluded.

		All sample (n = 11 868)	Excluded (n = 7707)	Included (n = 4161)	Test	p
Age (months; mean/sd)		118.98 (7.50)	119.07 (7.52)	118.82 (7.46)	$t = 1.72$	0.086
PDS score (mean/sd)		1.94 (0.82)	1.99 (0.83)	1.84 (0.77)	$t = 10.1$	<0.001
Birth weight (kg; mean/sd)		3.19 (0.66)	3.16 (0.69)	3.22 (0.61)	$t = -4.68$	<0.001
Weeks premature (mean/sd)		2.49 (42.00)	3.45 (52.08)	0.72 (1.85)	$t = 4.59$	0.001
BMI (kg/m ² ; mean/sd)		18.75 (4.08)	19.85 (4.62)	16.78 (1.44)	$t = 53.00$	<0.001
BMI percentile (mean/sd)		61.01 (30.71)	67.62 (32.34)	48.84 (22.91)	$t = 36.63$	<0.001
Weight class status (n, %)	Healthy weight	8124 (68.5)	3963 (51.4)	4161 (100.0)	$\chi^2 = 2952.95$	<0.001
	Overweight	1771 (14.9)	1771 (23.0)	0 (0.0)		
	Obesity	1973 (16.6)	1973 (25.6)	0 (0.0)		
Sex (n, %)	Female	5677 (47.8)	3568 (46.3)	2109 (50.7)	$\chi^2 = 20.51$	<0.001
	Male	6188 (52.1)	4136 (53.7)	2052 (49.3)		
	Intersex	3 (0.0)	3 (0.0)	0 (0.0)		
Puberty group (n, %)	Pre-puberty	5568 (46.9)	3382 (43.9)	2186 (52.5)	$\chi^2 = 80.90$	<0.001
	Puberty	6300 (53.1)	4325 (56.1)	1975 (47.5)		
Preterm (n, %)	Term	10 576 (89.1)	6871 (89.2)	3705 (89.0)	$\chi^2 = 2.16$	0.142
	Pre-term	1226 (10.3)	770 (10.0)	456 (11.0)		
	Missing	66 (0.6)	66 (0.9)	0 (0.0)		
Delivery mode (n, %)	Vaginal	6120 (51.6)	3371 (43.7)	2749 (66.1)	$\chi^2 = 98.97$	<0.001
	Caesarean	3686 (31.1)	2275 (29.5)	1411 (33.9)		
	Do not know	83 (0.7)	82 (1.1)	1 (0.0)		
	Missing	1979 (16.7)	1979 (25.7)	0 (0.0)		
Pregnancy issues (n, %)	Yes	3471 (29.2)	2082 (27.0)	1389 (33.4)	$\chi^2 = 197.47$	<0.001
	No	5867 (49.4)	3181 (41.3)	2686 (64.6)		
	Do not know	551 (4.6)	465 (6.0)	86 (2.1)		
	Missing	1979 (16.7)	1979 (25.7)	0 (0.0)		
Birth complications (n, %)	Yes	2270 (19.1)	1323 (17.2)	947 (22.8)	$\chi^2 = 44.26$	<0.001
	No	7190 (60.6)	4091 (53.1)	3099 (74.5)		
	Do not know	429 (3.6)	314 (4.1)	115 (2.8)		
	Missing	1979 (16.7)	1979 (25.7)	0 (0.0)		
Race (n, %)	Asian	243 (2.0)	157 (2.0)	86 (2.1)	$\chi^2 = 148.4$	<0.001
	Black	1869 (15.7)	1415 (18.4)	454 (10.9)		
	Mixed	1467 (12.4)	968 (12.6)	499 (12.0)		
	Other	525 (4.43)	370 (4.8)	155 (3.7)		
	NHPI/AINA	77 (0.6)	56 (0.7)	21 (0.5)		
	White	7517 (63.3)	4619 (59.9)	2898 (69.6)		
	Unknown/refused	146 (1.2)	105 (1.4)	41 (1.0)		
Missing	24 (0.2)	17 (0.2)	7 (0.2)			

(Continues)

TABLE 2 | (Continued)

		All sample (n = 11 868)	Excluded (n = 7707)	Included (n = 4161)	Test	p
Ethnicity (n, %)	Hispanic	2410 (20.3)	1667 (21.6)	743 (17.9)	$\chi^2 = 30.34$	< 0.001
	Non-Hispanic	9305 (78.4)	5929 (76.9)	3376 (81.1)		
	Unknown/refused	143 (1.2)	106 (1.4)	37 (0.9)		
	Missing	10 (0.1)	5 (0.1)	5 (0.1)		
Education (n, %)	<HS	593 (5.0)	460 (6.0)	133 (3.2)	$\chi^2 = 277.40$	< 0.001
	HS/GED	1132 (9.5)	855 (11.1)	277 (6.7)		
	Some college	3074 (25.9)	2209 (28.7)	865 (20.8)		
	Bachelor	3013 (25.4)	1842 (23.9)	1171 (28.1)		
	Postgrad	4042 (34.1)	2327 (30.2)	1715 (41.2)		
	Missing	14 (0.1)	14 (0.2)	0 (0.0)		
	Household income (n, %)	< 50 000\$	3222 (27.1)	2390 (31.0)		
50 000\$–100 000\$	3068 (25.9)	1954 (25.4)	1114 (26.8)			
> 100 000\$	4561 (38.4)	2659 (34.5)	1902 (45.7)			
Unknown/refused	1015 (8.6)	702 (9.1)	313 (7.5)			
Missing	2 (0.0)	2 (0.0)	0 (0.0)			
Breastfeeding (n, %)	No breastfed	1997 (16.8)	1395 (18.1)	602 (14.5)	$\chi^2 = 88.05$	< 0.001
	< 6 months	3373 (28.4)	1979 (25.7)	1394 (33.5)		
	> 6 months	6498 (54.8)	4333 (56.2)	2165 (52.0)		

Note: Continuous variables are presented as mean and standard deviation. Categorical variables are presented as frequency and percentage. Continuous variables were compared with student's *t*-test (*t*). Categorical variables were compared with chi-square tests (χ^2). Puberty classification is calculated using the PDS (Pubertal Developmental Scale) scores, which offers Tanner-stage like interpretation and is only provided for interpretation of sample characteristics: pre-puberty (PDS = 1) and puberty (PDS scores of 2 through 4). Race (collapsed into 6 groups) and ethnicity (collapsed into 2 groups) were self-reported by the caregiver and only for interpretation of sample diversity. Birth complications (not requiring hospitalisation) refer to any of the following: cyanosis, did not breath/needed oxygen, slow heart-beat, convulsions, jaundice, required blood transfusion. Pregnancy issues refer to any of the following: severe nausea and vomiting past 2nd trimester accompanied with weight loss, heavy bleeding requiring bed rest or treatment, pre-eclampsia, eclampsia, toxemia, gall bladder attack, proteinuria, rubella, severe anaemia, urinary-tract infections, gestational diabetes, high-blood pressure, previa abruptio, accident or injury requiring medical care. Abbreviations: AINA/NHPI, American Indian/Native American, Native Hawaiian/Pacific Islander; HS, high-school graduate; HS/HED, generalised education degree.

breastfed 6 months or less, those who were breastfed for more than 6 months had a lower BMI increase throughout puberty. Sex-stratified analyses echoed the previous results in boys ($\beta = -0.11$, 95% CI = $-0.19, -0.04$, $p = 0.004$), but not in girls ($\beta = -0.04$, 95% CI = $-0.10, 0.01$, $p = 0.128$). See Figure 2 (panels D-F) for a graphical representation of these results.

4.5 | Is Breastfeeding Associated With a Lower Risk of Transitioning to Unhealthy Weight at Ages 11–12?

By the follow-up visit in year 2, 283 individuals transitioned to unhealthy weight (i.e., 10.0% to overweight and 0.8% to obesity, respectively). Across sexes, breastfeeding status was significantly associated with a lower risk of unhealthy weight (RR = 0.78, 95% CI = 0.64, 0.91, $p = 0.002$). Breastfed youth were 21.6% (95% CI = 9.3, 35.6) less likely to transition to unhealthy weight than formula-fed youth. This weighted logistic regression model presented an accuracy of 65.2%. The sex-stratified analysis revealed that breastfeeding status associations were only

present in boys (RR = 0.63, 95% CI = 0.48, 0.77, $p < 0.001$). That is, boys who were breastfed were 36.6% (95% CI = 23.0, 52.3) less likely to develop unhealthy weight at ages 11–12 than those who were never breastfed. This model significantly predicted unhealthy weight class 63.2% of the time. In contrast, breastfeeding status was not associated with changes in the risk of transitioning to unhealthy weight in girls (RR = 0.96, 95% CI = 0.75, 1.21, $p = 0.689$). See Figure 3 (panels A-C) for more details.

4.6 | Is Breastfeeding Duration Associated With a Lower Risk of Transitioning to Unhealthy Weight at Ages 11–12?

Regarding breastfeeding duration, across both sexes, only breastfeeding for more than 6 months was related to a 29.4% (95% CI = 18.1, 43.2) decrease in the risk of developing unhealthy weight at ages 11–12 (RR = 0.71, 95% CI = 0.57, 0.82, $p < 0.001$). This model accurately predicted unhealthy weight 64.8% of the time. However, sex-stratified results showed that, in boys, breastfeeding for 6 months or less vs. formula-feeding (RR = 0.77,

TABLE 3 | Demographic and other variables of interest of the entire sample across visits.

		Baseline (ages 9–10) N= 4161	Year 1 (ages 10–11) N= 3782	Year 2 (ages 11–12) N= 2643
Age (months; mean, sd)		118.82 (7.46)	130.84 (7.66)	142.84 (7.70)
PDS score (mean, sd)		1.84 (0.77)	2.19 (0.92)	2.62 (0.97)
Birthweight (kg; mean, sd)		3.22 (0.61)	3.23 (0.62)	3.22 (0.62)
Weeks premature (mean, sd)		0.72 (1.85)	0.73 (1.86)	0.75 (1.89)
BMI (kg/m ² ; mean, sd)		16.78 (1.44)	17.70 (1.93)	18.48 (2.15)
BMI percentile (mean, sd)		48.84 (22.91)	52.06 (24.25)	53.22 (24.60)
BMI group (n, %)	Healthy weight	4161 (100.0)	3447 (91.1)	2360 (89.3)
	Overweight	0 (0.0)	316 (8.4)	263 (10.0)
	Obesity	0 (0.0)	19 (0.5)	20 (0.8)
Sex (n, %)	Boy	2109 (50.7)	1915 (50.6)	1347 (51.0)
	Girl	2052 (49.3)	1867 (49.4)	1296 (49.0)
Pubertal stage (n, %)	Pre-puberty	2186 (52.5)	1456 (38.5)	606 (22.9)
	Puberty	1975 (47.5)	2326 (61.5)	2037 (77.1)
Preterm (n, %)	Term	3705 (89.0)	3365 (89.0)	2343 (88.6)
	Pre-term	456 (11.0)	417 (11.0)	300 (11.4)
Delivery mode (n, %)	Vaginal	2749 (66.1)	2478 (65.5)	1733 (65.6)
	C-section	1411 (33.9)	1303 (34.5)	909 (34.4)
	Unknown	1 (0.0)	1 (0.0)	1 (0.0)
Pregnancy issues (n, %)	Yes	1389 (33.4)	1249 (33.0)	843 (31.9)
	No	2686 (64.6)	2458 (65.0)	1757 (66.5)
	Unknown	86 (2.1)	75 (2.0)	43 (1.6)
Birth issues (n, %)	Yes	947 (22.8)	863 (22.8)	579 (21.9)
	No	3099 (74.5)	2809 (74.3)	1994 (75.4)
	Do not know	115 (2.8)	110 (2.9)	70 (2.6)
Race (n, %)	Asian	86 (2.1)	74 (2.0)	55 (2.1)
	Black	454 (10.9)	390 (10.3)	230 (8.7)
	Mixed	499 (12.0)	444 (11.8)	289 (10.9)
	Other	155 (3.7)	136 (3.6)	99 (3.8)
	NHPI/AINA	21 (0.5)	20 (0.5)	15 (0.6)
	White	2898 (69.6)	2683 (70.9)	1922 (72.7)
	Unknown/Refused	41 (1.0)	28 (0.7)	28 (1.1)
Ethnicity (n, %)	Hispanic	743 (17.9)	636 (16.8)	434 (16.4)
	Non-Hispanic	3376 (81.1)	3111 (82.3)	2183 (82.6)
	Unknown/Refused	37 (0.9)	30 (0.8)	23 (0.9)
	Missing	5 (0.1)	5 (0.1)	3 (0.1)

(Continues)

TABLE 3 | (Continued)

		Baseline (ages 9–10) N= 4161	Year 1 (ages 10–11) N= 3782	Year 2 (ages 11–12) N= 2643
Education (n, %)	<HS	133 (3.2)	103 (2.7)	69 (2.6)
	HS/GED	277 (6.7)	231 (6.1)	148 (5.6)
	Some college	865 (20.8)	770 (20.4)	525 (19.9)
	Bachelor	1171 (28.1)	1068 (28.2)	785 (29.7)
	Postgrad	1715 (41.2)	1610 (42.6)	1116 (42.2)
Household income (n, %)	< 50 000\$	832 (20.0)	716 (18.9)	492 (18.6)
	50 000\$–100 000\$	1114 (26.8)	1023 (27.0)	749 (28.3)
	> 100 000\$	1902 (45.7)	1780 (47.1)	1225 (46.3)
	Unknown/Refused	313 (7.5)	263 (7.0)	177 (6.7)
Breastfeeding (n, %)	Not breastfed	602 (14.5)	516 (13.6)	358 (13.5)
	< 6 months	1394 (33.5)	1263 (33.4)	892 (33.7)
	≥ 6 months	2165 (52.0)	2003 (53.0)	1393 (52.7)

Note: Continuous variables are presented as mean and standard deviation. Categorical variables are presented as frequency and percentage. Puberty classification is calculated using the PDS (Pubertal Developmental Scale) scores, which offer Tanner-stage like interpretation and only provided for interpretation of sample characteristics: pre-puberty (PDS = 1) and puberty (PDS scores of 2 through 4). Race (collapsed into 6 groups) and ethnicity (collapsed into 2 groups) were self-reported by the caregiver and only for the interpretation of sample diversity. Birth complications (not requiring hospitalisation) refer to any of the following: cyanosis, did not breath/needed oxygen, slow heart-beat, convulsions, jaundice, required blood transfusion. Pregnancy issues refer to any of the following: severe nausea and vomiting past 2nd trimester accompanied with weight loss, heavy bleeding requiring bed rest or treatment, pre-eclampsia, eclampsia, toxemia, gall bladder attack, proteinuria, rubella, severe anaemia, urinary-tract infections, gestational diabetes, high-blood pressure, previa abruptio, accident or injury requiring medical care. Abbreviations: AINA/NHPI, American Indian/Native American, Native Hawaiian/Pacific Islander; HS, high-school graduate; HS/HED, generalised education degree.

95% CI=0.57, 0.97, $p=0.027$) and breastfeeding for more than 6 months relative to the previous two levels (RR=0.52, 95% CI=0.38, 0.63, $p<0.001$) was significantly associated with a lower risk of unhealthy weight.

Specifically, being breastfed for 6 months or less was associated with a risk reduction of 23.2% (95% CI=3.34, 42.4), whilst being breastfed for more than 6 months was associated with a decrease of 48.2% (95% CI=36.7, 62.4). This model predicted unhealthy weight with a 62.0% accuracy. No results were found in girls for either contrast one ($p=0.756$) or two ($p=0.668$). See Figure 3 (panels D-F) for a graphical representation of the breastfeeding duration relative to the risk of developing unhealthy weight at ages 11–12.

5 | Discussion

This study examined the longitudinal associations of breastfeeding, weight gain, and the risk of transition to obesity during adolescence, one of the most critical periods of development.³ Unlike prior research, the current study was conducted in a cohort of youth considered to be of healthy weight at baseline, allowing examination of the temporal order of this relationship. Here, we also aimed to clarify how chronological maturation (age) and biological maturation (puberty) independently influence the relationship between breastfeeding and weight gain. We showed that breastfeeding for more than 6 months was associated with lower BMI trajectories in boys and girls when considered in the context of development (ageing), but only in boys when focusing on biological maturation (puberty advances). With regard to breastfeeding associations with the risk of

transitioning to unhealthy weight at ages 11–12, our results indicated that breastfed boys were less likely to develop overweight and obesity, especially with longer breastfeeding duration. Our results highlight the importance of breastfeeding due to its enduring, dose-dependent associations with healthy weight development during adolescence, a period of increased obesity risk.

Our findings showed that breastfeeding was associated with reduced BMI trajectories from late childhood to early adolescence (9–12 years old). This is important because, during puberty, the risk of developing obesity is higher due to increased appetite and intake of calories [4]. This finding thus demonstrates that the association between breastfeeding and healthy weight extends into this window. However, since age may not accurately reflect maturation during puberty [34], we also examined the relationship between breastfeeding and weight across different stages of puberty. Results suggested that breastfeeding was related to lower weight gain across pubertal stages, but this association was only present in boys. Although sex differences were surprising, these may in part be explained by our study design. Baseline assessments showed that most girls (57.8%) were at some stage of puberty compared to boys, who were still largely pre-pubertal (86.6%). This aligns with prior research indicating that girls enter puberty earlier than boys [23]. Since puberty is a risk factor for weight gain, and because girls experience puberty earlier than boys [23], it is possible that some girls may have already experienced weight gain by the time they enrolled in the study. In other words, we might not have been able to capture how pubertal onset influenced BMI changes in girls as we did in boys. Another potential explanation for this inconsistency could be related to

TABLE 4 | Comparison of sample characteristics at baseline based on breastfeeding status.

		Breastfed (n = 3559)	Not breastfed (n = 602)	Test	p
Age (months; mean, sd)		118.85 (7.51)	118.60 (7.16)	$t = 0.81$	0.435
PDS score (mean, sd)		1.80 (0.75)	2.09 (0.85)	$t = -7.95$	<0.001
Birth weight (kg; mean, sd)		3.25 (0.61)	3.08 (0.62)	$t = 5.95$	<0.001
Weeks premature (mean, sd)		0.69 (1.82)	0.91 (2.01)	$t = -2.53$	0.006
BMI (kg/m ² ; mean, sd)		16.76 (1.43)	16.91 (1.47)	$t = -2.25$	0.022
BMI percentile (mean, sd)		48.47 (22.79)	51.06 (23.47)	$t = -2.52$	0.01
Child sex (n, %)	Boy	1801 (50.6)	308 (51.2)	$\chi^2 = 0.04$	0.834
	Girl	1758 (49.4)	294 (48.8)		
Puberty stage (n, %)	Pre-puberty	1953 (54.9)	233 (38.7)	$\chi^2 = 61.22$	<0.001
	Puberty	1606 (45.1)	369 (61.3)		
Preterm (n, %)	Term	3187 (89.5)	518 (86.0)	$\chi^2 = 6.11$	0.013
	Pre-term	372 (10.5)	84 (14.0)		
Mode of delivery (n, %)	Vaginal	2380 (66.9)	369 (61.3)	$\chi^2 = 12.78$	0.002
	C-section	1179 (33.1)	232 (38.5)		
	Unknown/Refused	0 (0.0)	1 (0.2)		
Pregnancy issues (n, %)	Yes	1123 (31.6)	266 (44.2)	$\chi^2 = 36.98$	<0.001
	No	2361 (66.3)	325 (54.0)		
	Unknown/Refused	75 (2.1)	11 (1.8)		
Birth issues (n, %)	Yes	834 (23.4)	113 (18.8)	$\chi^2 = 6.53$	0.038
	No	2629 (73.9)	470 (78.1)		
	Unknown/Refused	96 (2.7)	19 (3.2)		
Race (n, %)	Asian	76 (2.1)	10 (1.7)	$\chi^2 = 291.26$	<0.001
	Black	269 (7.6)	185 (30.9)		
	Mixed	444 (12.5)	55 (9.1)		
	Other	134 (3.8)	21 (3.5)		
	NHPI/AINA	16 (0.4)	5 (0.8)		
	White	2579 (72.5)	319 (53.3)		
	Unknown/Refused	38 (1.1)	3 (0.5)		
Ethnicity (n, %)	Hispanic	631 (17.7)	112 (18.6)	$\chi^2 = 0.29$	0.863
	Non-Hispanic	2892 (81.4)	484 (80.5)		
	Unknown/Refused	32 (0.9)	5 (0.8)		
	Unknown	4 (0.1)	1 (0.2)		
	Missing	3 (0.1)	4 (0.7)		
Education (n, %)	Less than HS	82 (2.3)	51 (8.5)	$\chi^2 = 368.52$	<0.001
	HS/GED	164 (4.6)	113 (18.8)		
	Some college	662 (18.6)	203 (33.7)		
	Bachelor	1062 (29.8)	109 (18.1)		
	Postgrad	1589 (44.6)	126 (20.9)		

(Continues)

TABLE 4 | (Continued)

	Breastfed (n = 3559)	Not breastfed (n = 602)	Test	p
Income (n, %)			$\chi^2 = 203.84$	<0.001
	< 50 000\$	606 (17.0)		
	50 000\$–100 000\$	966 (27.1)		
	> 100 000\$	1752 (49.2)		
	Unknown/Refused	235 (6.6)		

Note: Continuous variables are presented as mean and standard deviation. Categorical variables are presented as frequency and percentage. Continuous variables were compared with student's *t*-test (*t*). Categorical variables were compared with chi-square tests (χ^2). Puberty classification is calculated using the PDS (Pubertal Developmental Scale) scores, which offers Tanner-stage like interpretation and is only provided for interpretation of sample characteristics: pre-puberty (PDS = 1) and puberty (PDS scores of 2 through 4). Race (collapsed into 6 groups) and ethnicity (collapsed into 2 groups) were self-reported by the caregiver and only for the interpretation of sample diversity. Birth complications (not requiring hospitalisation) refer to any of the following: cyanosis, did not breath/needed oxygen, slow heart-beat, convulsions, jaundice, required blood transfusion. Pregnancy issues refer to any of the following: severe nausea and vomiting past 2nd trimester accompanied with weight loss, heavy bleeding requiring bed rest or treatment, pre-eclampsia, eclampsia, toxemia, gall bladder attack, proteinuria, rubella, severe anaemia, urinary-tract infections, gestational diabetes, high-blood pressure, previa abruptio, accident or injury requiring medical care. Abbreviations: AINA/NHPI, American Indian/Native American, Native Hawaiian/Pacific Islander; HS, high-school graduate; HS/HED, generalised education degree.

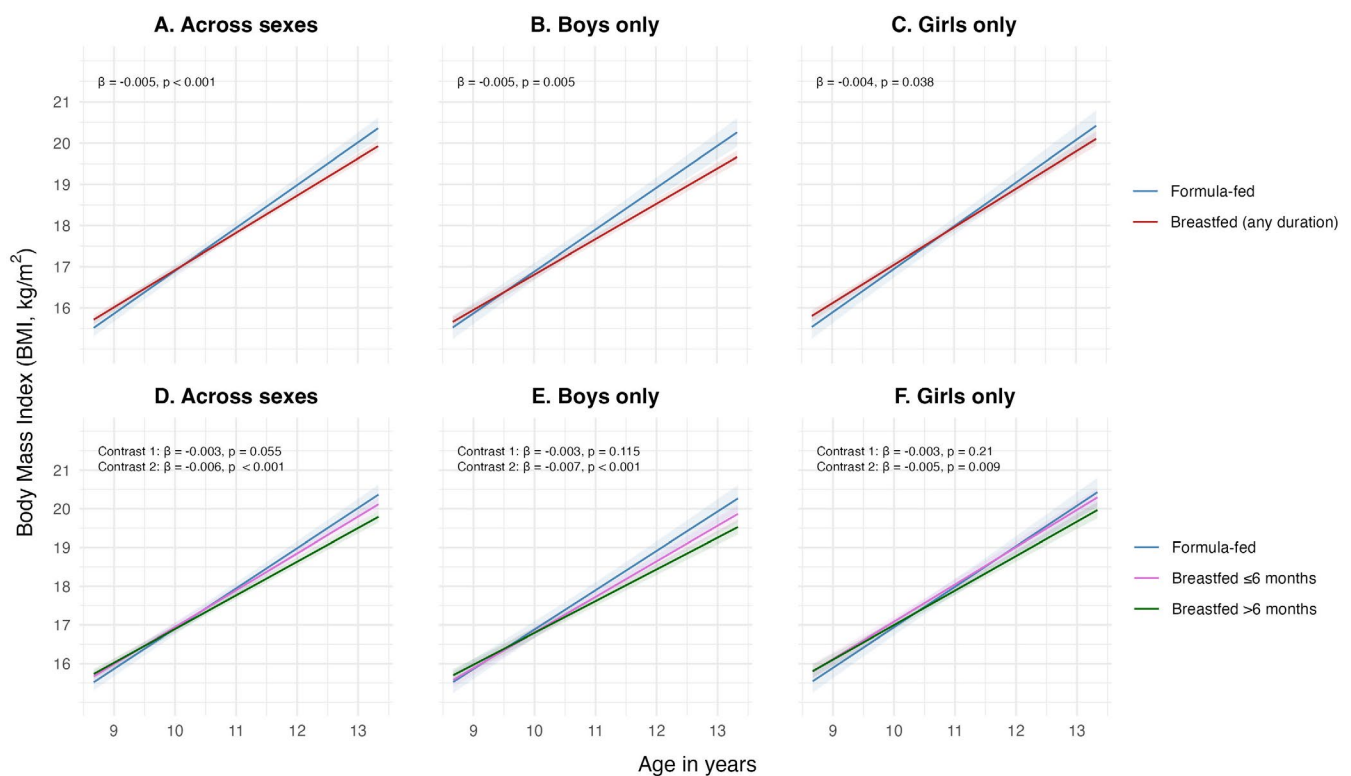


FIGURE 1 | The top panel shows the results of the two-way interaction between breastfeeding status and age (*x*-axis) in predicting body mass index (BMI, *y*-axis). Results are presented across sexes (A) and separately for boys (B) and girls (C). The bottom panel shows the results of the two-way interaction between breastfeeding duration and age (*x*-axis) in predicting BMI (*y*-axis). Results are presented across sexes (D), and separately for boys (E) and girls (F). Contrast 1 represents the comparison between the slopes of those who were breastfed for 6 months or less vs. not breastfed. Contrast 2 indicates the comparison between the slopes of those who were breastfed for more than 6 months vs. the average of the two previous slopes. Shaded areas around each line represent 95% confidence intervals. Note: Whilst the analysis was conducted using age in months (centred), the *x*-axis was modified to approximate age in years.

how puberty was measured in this study. In some instances, Tanner-stage-like reports do not perfectly align with actual biology, especially when parents or youth are the ones reporting [35–37]. Altogether, our findings suggest that, irrespective of sex and puberty, breastfeeding is associated with healthier BMI trajectories from late childhood (ages 9–10) to early adolescence (ages 11–12).

Whilst a recent meta-analysis showed that breastfeeding was associated with decreased rates of obesity [2], most of the included studies were limited to early childhood, with only two following children up to age 6 years old [38, 39]. This raises the question of whether breastfeeding associations remain effective at later stages of development. Although a recent study did investigate this in children and adolescents, it included individuals with obesity,

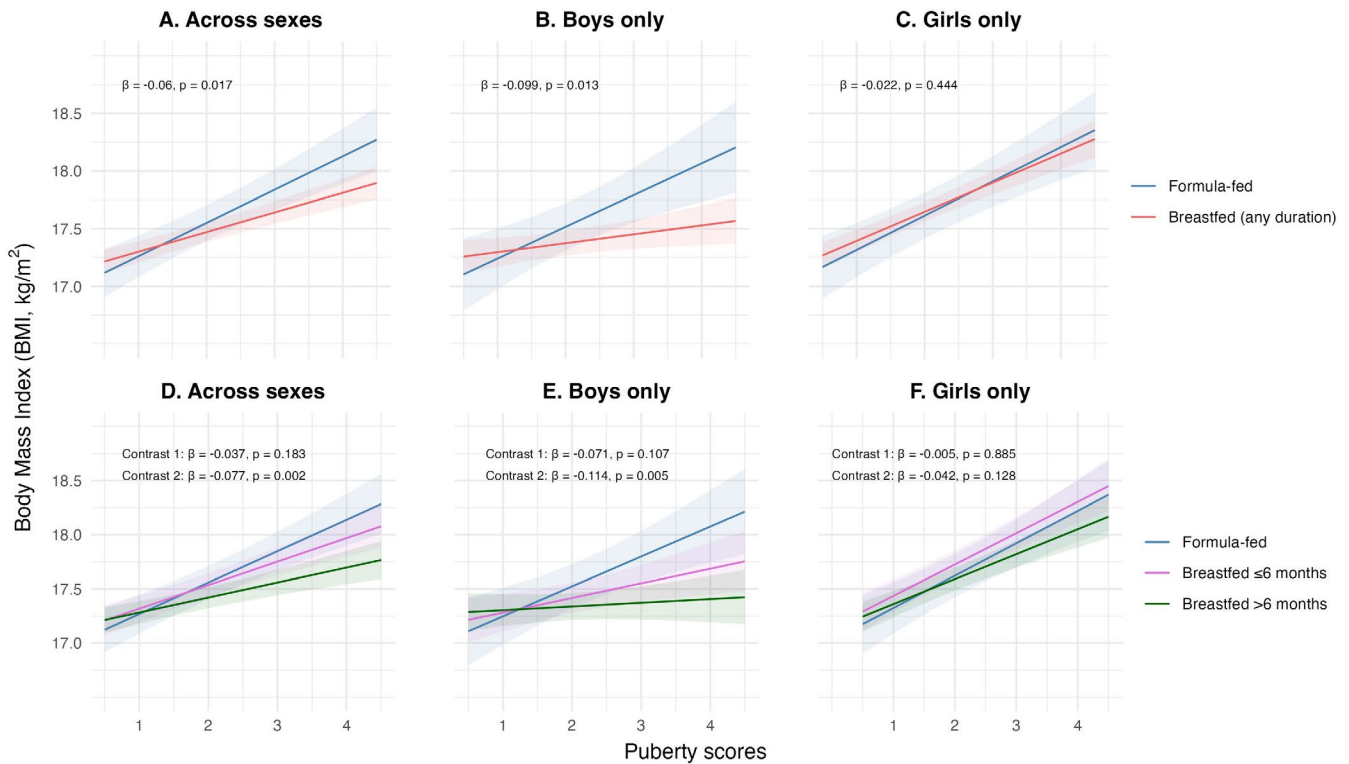


FIGURE 2 | The top panel shows the results of the two-way interaction between breastfeeding status (slopes) and puberty (x-axis) in predicting body mass index (BMI, y-axis), first across sexes (A), and separately for boys (B) and girls (C). The bottom panel shows the results of the two-way interaction between breastfeeding duration (slopes) and puberty (x-axis) in predicting BMI (y-axis). Results are also presented by sex. Results are presented across sexes (D), and separately for boys (E) and girls (F). Contrast 1: Comparison between breastfed for 6 months or less vs. not breastfed. Contrast 2: Comparison between breastfed for more than 6 months vs. the average of not breastfed and breastfed for 6 months or less. Shaded areas around each line represent 95% confidence intervals.

which prevents any investigation regarding temporal associations [18]. Here, using a sample that did not include participants with overweight or obesity at baseline, we found that boys who were breastfed, regardless of the amount, showed a 29.4% risk reduction in the likelihood of developing unhealthy weight at ages 11–12 years old. It is worth noting that this association was linear, or dose-dependent. That is, boys who were breastfed 6 months or less showed a 23.2% reduction, whilst those who were breastfed more than 6 months exhibited a 48.2% reduction. Again, we did not expect breastfeeding to provide protection exclusively for boys. These findings highlight the need for more research concerning sex differences in pubertal onset and the risk of obesity, and especially studies that include girls who have not yet started puberty.

Although numerous mechanisms are at play, breast milk is believed to help shape metabolic systems early in life, enhancing sensitivity to hunger and satiety signals [7, 40, 41]. Breast milk is a complex mixture of hundreds of bioactive molecules, including leptin and adiponectin, hormones that indicate energy reserves and prevent overeating [42]. In contrast, many infant formulas, especially lactose-reduced or lactose-free formulas, are produced with added sugars (e.g., corn syrup solids, sucrose) and generally contain more protein than breast milk. These factors have been associated with accelerated weight gain and obesity, as shown by both meta-analysis [9] and original work [10, 11]. Additionally, feeding practices further

contribute to these differences: breastfeeding is self-regulated by the infant, whereas bottle-feeding is regulated by the caregiver, which can constitute a missed opportunity for the child to learn aligning intake with internal hunger and satiety cues [8]. Research has shown that children predominantly fed from a bottle were twice as likely to empty the bottle or cup later in life [12]. In other words, bottle-fed children are more prone to overeating than breastfed children. Similarly, the early introduction of solid foods, which often coincides with shorter breastfeeding duration [43], has also been associated with a higher risk of obesity [44]. This is not only because eating is, like bottle-feeding, externally regulated, but because solid foods tend to be more energy-dense and offer less variety in taste than breast milk. This could contribute to shaping long-term dietary preferences towards mass-produced flavours, which are typically higher in calories. In support of this, recent research has shown that breastfed infants are more likely to try new foods [45] and consume more vegetables and drink fewer sugar-sweetened beverages [46]. This is relevant to our study because as youth age, they become more independent about their dietary choices. Altogether, these biological and behavioural mechanisms suggest that breastfeeding and breast milk may better equip children to eat on demand and more diversely, which could help explain why, during a period in life marked by increased appetite and dietary independence, like puberty, breastfed youth showed healthier BMI trajectories and a lower risk of developing unhealthy weight.

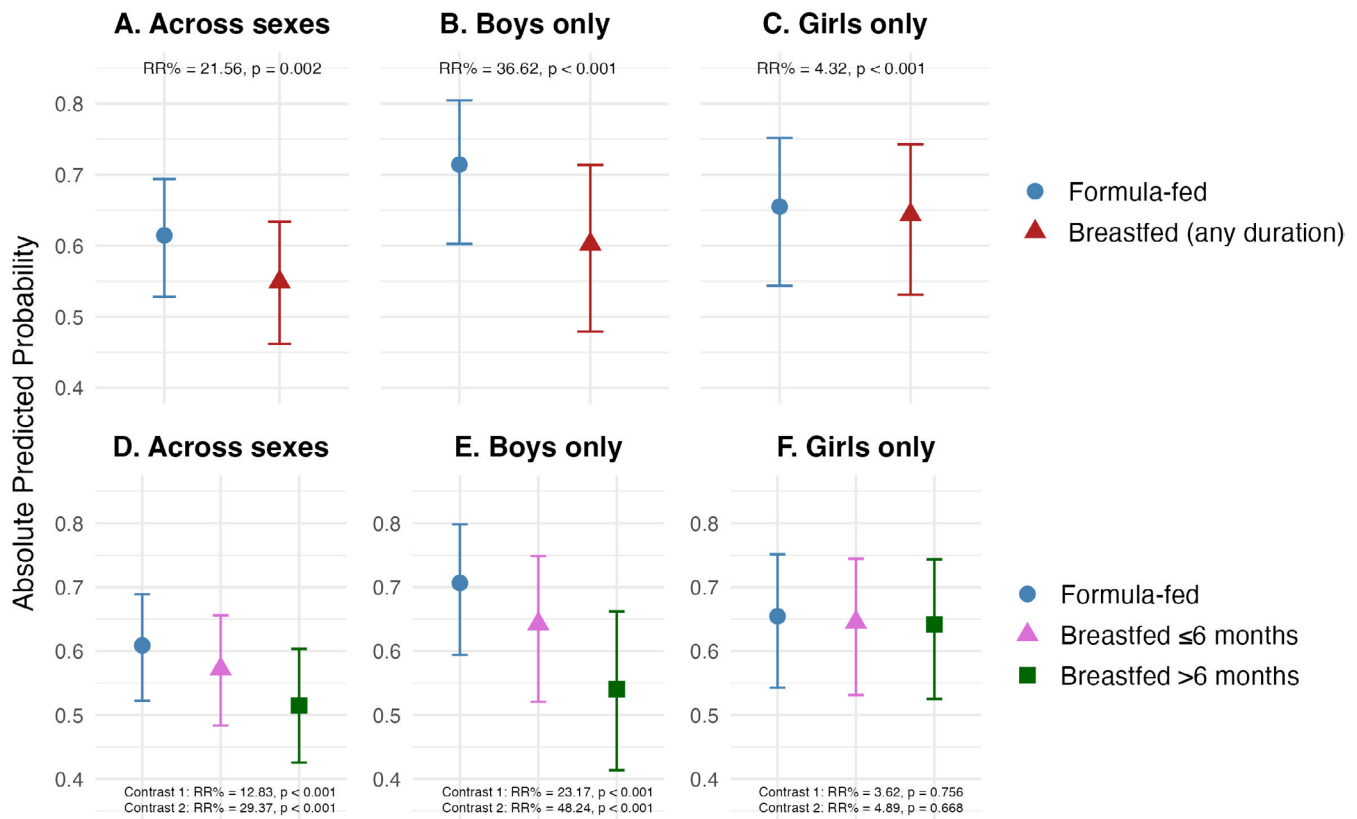


FIGURE 3 | The top panel shows the influence of breastfeeding status on the absolute probability (y-axis) of transition to the unhealthy weight group at ages 11–12 across sexes (A), in boys (B), and girls (C). The bottom panel shows the association between breastfeeding duration and the absolute probability of transitioning to the unhealthy weight category at ages 11–12 across sexes (D), and separately for boys (E) and girls (F). $RR\% = (1 - \text{Relative Risk}) \times 100$.

Our current work has several strengths that we would like to highlight. By focusing on youth who had not yet developed overweight or obesity at baseline, we were able to examine how breastfeeding related to subsequent weight development during adolescence. The use of repeated weight assessments provided temporal information that strengthened inferences about body weight development. This study also leveraged a large and diverse sample, further enhancing the robustness and generalizability of the findings. In addition, we considered potential sex differences in weight trajectories by stratifying analyses and incorporating puberty scores as a more accurate proxy of biological maturation than age.

This study has several limitations as well. The ABCD Study did not collect information on breastfeeding modalities, precluding differentiation between exclusive and mixed breastfeeding (i.e., breastfeeding combined with formula and/or solid foods). Breastfeeding duration was reported retrospectively, introducing the potential for recall bias. No data were collected on breast milk composition, limiting the ability to examine specific biological components. In addition, maternal exposures during lactation (e.g., diet, lifestyle factors such as alcohol or tobacco use) affect breast milk composition, but such data were not available in the ABCD Study. Future research should incorporate these and other factors to better understand the mechanisms linking breastfeeding and child outcomes. Although this study explores longitudinal associations between breastfeeding and BMI trajectories and status, causality cannot be determined. The study

used BMI data, so more comprehensive adiposity assessments are warranted in future studies. Some analyses in this study (e.g., transition to unhealthy weight at ages 11–12) used standardised BMI scores based on CDC growth charts [22], which, besides being discouraged for longitudinal analysis [30], present several other methodological flaws, including non-linear scaling, compression at the extremes of the distribution (floor/ceiling effects), and potential biases related to race and socioeconomic factors. More importantly, body weight development is a complex and multifaceted process. Therefore, future studies should aim to use more precise measurements of body fat, which may more accurately reflect metabolic changes. Although several covariates were considered, unmeasured factors such as the timing of solid food introduction, diet, and physical activity might also have impacted the observed associations. To assess the potential influence of unmeasured confounders, we calculated E-values for our results on unhealthy weight transition at ages 11–12. The E-value estimates the strength of an unmeasured confounder required to account for the observed association [47]. E-values ranged from 1.88 to 2.55, indicating robustness against unmeasured confounders. Although the study included a geographically diverse sample, it was skewed towards higher-income families, which might not fully represent the broader population in terms of breastfeeding and weight gain patterns [48]. Additionally, our sample selection may have introduced biases because we excluded youth with overweight and obesity at baseline to focus on studying the natural progression of weight gain without the confounding influence of current overweight

and obesity. We note that some individuals who historically are more prone to obesity (e.g., those identifying as Black, Hispanic/Latinx, low socioeconomic status [49]) may have been excluded from our sample, and as such, reduced the diversity of our sample. Youth assessed after the COVID-19 lockdown were also excluded to minimise the confounding effect of weight gain due to involuntary sedentarism during this period, which may have reduced statistical power. Whilst most boys were prepubescent at baseline (86.6%), the majority of girls were at some stage of puberty (57.8%), which prevented examining both sexes at the same developmental stage. Additionally, the pubertal assessment relied on self- or caregiver report, which can be affected by misinterpretation of visual cues, sex-specific reporting biases (i.e., boys tend to overestimate, and girls underestimate their pubertal stages), and age-related tendencies to report values closer to the average (i.e., regression to the mean) [35–37].

In summary, this study examined the associations between breastfeeding and weight trajectories, as well as the risk of overweight and obesity, across puberty. In a large, diverse sample of initially healthy-weight youth, longer breastfeeding duration was associated with lower BMI trajectories over time. Notably, amongst boys, breastfeeding was related to lower BMI trajectories throughout puberty and decreased risk of developing overweight or obesity by ages 11–12. These findings highlight the potential long-term benefits of breastfeeding for healthy weight development and support public health efforts to promote breastfeeding as part of early obesity prevention strategies. However, as this study is observational, these associations should be interpreted with caution, and causal relationships should be confirmed in experimental settings. Future research should aim to include a sample that is balanced in terms of puberty to better understand the sex-specific patterns we revealed in this study.

Acknowledgements

We would like to thank the participants of the ABCD Study and the research assistants who collected the data. We also thank the institutions who made this work possible through funding. Jonatan Ottino González was supported by funding by The Saban Research Institute at Children's Hospital Los Angeles (RCDF-2024-000016305). Shana Adise was supported by funding from the NIH NIDDK (K01 DK135847), The Southern California Center for Latino Health (Funded by The National Institute on Minority Health and Health Disparities, P50MD017344), and funding by The Saban Research Institute at Children's Hospital of Los Angeles. The ABCD Study is supported by the National Institutes of Health and National Institute on Drug Abuse and additional federal partners under award numbers U01DA041048, U01DA050989, U01DA051016, U01DA041022, U01DA051018, U01DA051037, U01DA050987, U01DA041174, U01DA041106, U01DA041117, U01DA041028, U01DA041134, U01DA050988, U01DA051039, U01DA041156, U01DA041025, U01DA041120, U01DA051038, U01DA041148, U01DA041093, U01DA041089, U24DA041123, U24DA041147. A full list of supporters is available at <https://abcdstudy.org/federal-partners/>. This manuscript reflects the authors' views and may not reflect the opinions or views of the NIH, the Southern California Center for Latino Health, The Saban Research Institute, or other ABCD Study consortium investigators. Jonatan Ottino González wrote the manuscript, conducted the analyses, and interpreted the data under Shana Adise's guidance. Sevan Esaian and Shana Adise provided input on the statistical analyses. Miguel Angel Rivas Fernández, Sevan Esaian, Michael I. Goran,

Shana Adise, and Jonatan Ottino González contributed important intellectual content. All authors critically revised the manuscript and approved its final version. The ABCD Study consortium investigators designed and implemented the study and/or provided data but did not necessarily participate in the analyses or writing of this work.

Funding

This work was supported by Saban Research Institute (RCDF-2024-000016305), National Institute of Diabetes and Digestive and Kidney Diseases (K01 DK135847), The National Institute on Minority Health and Health Disparities (P50MD017344), National Institutes of Health (U01DA041048, U01DA050989, U01DA051016, U01DA041022, U01DA051018, U01DA051037, U01DA050987, U01DA041174, U01DA041106, U01DA041117, U01DA041028, U01DA041134, U01DA050988, U01DA051039, U01DA041156, U01DA041025, U01DA041120, U01DA051038, U01DA041148, U01DA041093, U01DA041089, U24DA041123, U24DA041147) and National Institute on Drug Abuse.

Conflicts of Interest

Michael I. Goran receives royalties for his book *Sugarproof: The Hidden Dangers of Sugar That Are Putting Your Child's Health at Risk and What You Can Do*, and is the scientific advisor for YUMI foods. The other authors declare no conflicts of interest.

Data Availability Statement

Data used in the preparation of this article were obtained from the ABCD Study (<https://abcdstudy.org/>), which is held in the NIMH Data Archive (NDA) and is publicly available. The ABCD Study data repository grows and changes over time. The ABCD Study data used in this report were obtained from <https://doi.org/10.15154/z563-zd24>. The code used to prepare, conduct the analysis, and plot the results can be found in: <https://github.com/Adise-lab/abcd-lactation-bmi.git>.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Breastfeeding status year 1 follow-up (ages 10–11). **Table S2:** Breastfeeding status year 2 follow-up (ages 11–12). **Table S3:** Breastfeeding duration in months at baseline (ages 9–10). **Table S4:** Breastfeeding duration in months year 1 follow-up (ages 10–11). **Table S5:** Breastfeeding duration year 2 follow-up (ages 11–12).