INTRODUCTION

Meta-analyses suggest that children who sleep less than their peers have an approximate doubling of risk for overweight and obesity, but the data informing this estimate are largely from older children and adolescents.1,2 As early childhood is considered a critical time-frame for obesity development,3,4 and associations between sleep and adiposity may differ by life stage due to alterations in sleep need and behaviour,5,6 more research in infants and toddlers is warranted to inform obesity prevention.

It is important that any such research acknowledges that there are sociocultural differences in child sleep duration (children of non-White ethnicity sleep less)7,8 and obesity risk.9 Childhood obesity prevalence is twice as high in the most compared to the least deprived areas in England, and is higher than the national average in ethnic minority groups,10 including UK resident South Asian children who are higher risk for cardiometabolic disease.11 Knowledge about sleep duration and its relation with adiposity in disadvantaged high-risk settings and ethnic groups is lacking, however, because most existing studies have incorporated homogenous groups of White young children from predominantly well-educated and high income families.12-16 Studies have also relied upon BMI as an indicator of total adiposity,9 which exhibits ethnic variation17 and is strongly related to a multitude of cardiovascular and metabolic risk factors more so than BMI.18,19

The relation between sleep duration and adiposity has also typically only been considered as unidirectional, although the association may run in both directions.13,15 Higher adiposity may promote sleep disorders (apnoea or insomnia)20,21 and may influence intermediary behaviours that could impede or aid sleep (e.g. physical activity).22,23 Research is needed to identify if adiposity constitutes a novel and potentially modifiable determinant of childhood sleep, given that adequate sleep is essential for normal development and functioning.24 Child sleep duration exhibits long-term stability,25 and there has been a prevailing trend of declining childhood sleep in the last 2 decades26 that may have been most pronounced in younger children.27

To address current gaps in the literature, this study examined the associations between sleep duration with total and abdominal adiposity using data from four time-points in early childhood (collected at about age 12, 18, 24 and 36 months) in a biethnic sample of South Asian and White children from a deprived location. Possible bidirectionality of these associations was also scrutinised. Information of this type could help to address health inequalities and the higher prevalence of obesity and cardiometabolic disease in South Asian populations.28,29
METHODS

Study Design and Population
All procedures, including equipment details, are described thoroughly elsewhere. Briefly, this investigation entailed data from a sub-study of the “Born in Bradford” (BiB) cohort, named BiB-1000. Expectant mothers (n = 1916) at 26–28 weeks gestation were approached to participate in the study when attending routine hospital appointments in 2008–09; 1735 accepted (90.6% uptake) and five measurement rounds were carried out when children were about age 6, 12, 18, 24 and 36 months. Attendance at each time-point ranged between 70–77%, 47% of participants attended every time-point, and 17% were formally withdrawn from the study by 36 months. The BiB-1000 cohort is comparable to the larger BiB cohort which is representative of Bradford, the sixth largest and one of the most deprived and ethnically diverse UK cities. At the time of recruitment, 60% of all babies in Bradford were born into the poorest 20% of locations in England and Wales, and approximately half of all newborns in Bradford are of South Asian origin (mainly Pakistani heritage). Only children from singleton births (n = 1707) were included in this investigation as we relied on parent-reports of child behaviours, which may have been compromised for twins. Furthermore, because sleep characteristics and circadian rhythmicity take approximately 12 months to mature, it has been recommended that sleep analyses should be based only on sleeping patterns established after age one year. For this reason the sample was restricted to participants with data for sleep duration, body composition and potential confounders from the 12 month time-point onwards (n = 411). For the purposes of this investigation the 12 month time-point is referred to as baseline. Due to small numbers, children with a mother belonging to an ethnic group other than South Asian (Pakistani, Indian, and Bangladeshi) or White (British or Other e.g. White European) were also excluded (remaining n = 1338).

Sleep Assessment
At all time-points the average number of hours usually slept by children between 6am to 6pm, and 6pm to 6am, were reported by parents in response to a single question administered by an interviewer. These data were combined to the average sleep duration in a 24h period, which correlated with concurrent parent-reported sleep diary data that were collected in a sub-sample of children at the 18 and 36 month assessments (n = 485; r = 0.44, p < 0.001). For description, the mean sleep duration over all measurement occasions was calculated and five a priori categories of sleep duration were derived based on recommended ranges (<11, 11–12, 12–13, 13–14 and ≥ 14 h/day). The middle category (12–13 h/day) reflects the average reported sleep duration of young children from England as well as children globally.

Anthropometric Measures
At all visits children’s weight and height were assessed by trained researchers. Body mass index (BMI) and z-scores were calculated. As in other aetiological studies the data were used to generate pooled estimates of body composition by aggregating estimates from published age-appropriate equations that have been validated in both South Asian and White children. For each equation, predicted total body water was first converted to fat-free mass using age- and sex-specific hydration factors and estimates of fat mass (weight minus fat-free mass) and percent body fat (fat mass/weight) were subsequently derived. Every parameter estimate was mean-averaged to create pooled fat mass and percent body fat variables. At every visit (but with varying amounts of missing data) waist circumferences at the level of the naval and skinfolds of the left triceps, subscapular and thigh were also measured, and the sum of skinfolds was calculated. Reliability metrics calculated for the researchers showed good intra- and inter-observer technical error of measurements for waist circumference and skinfolds.

Covariates
Potential confounders were chosen based on biological plausibility and evidence linking them with sleep duration and adiposity. Three socioeconomic status (SES) groups were derived from 19 indicators collated during interviews that were typically conducted with mothers. Maternal ethnicity (used as a proxy for child ethnicity), age and smoking in pregnancy were further reported at the point of recruitment and maternal height and weight were first measured; weight was repeated at every subsequent time-point and maternal BMI calculated. Number of previous births (used as a proxy for older siblings), child’s season of birth, gender, gestational age, and birth weight were extracted from medical records. Age introduced to solids was collected at the 6 and 12 month time-points, as was the number of weeks children were breast fed, for which information was further available at the 24 month visit. At the 24 month time-point, parents also reported the frequency with which children went to bed at a regular time (dichotomised as every day or not), and using parent responses to validated questions posed at 24 and 36 months, the levels of children’s moderate-to-vigorous physical activity were estimated. At all time-points, children’s mean daily TV-viewing after 6pm was calculated and was further combined with the hours before 6pm to provide an estimate of total TV-viewing. Infant dietary data were also collected using a validated food frequency questionnaire that was modified for BiB by including ethnic-specific foodstuffs. For this study, diet pattern constructs were formed to reflect unhealthy snacking (i.e. frequency of biscuit, crisps, cakes, sweets, chocolate, sugar-sweetened beverage consumption) and daily intakes of fruit and vegetables. To account for a small proportion of unlikely responses, values were capped at 10 snacks or 10 fruit/vegetable portions daily, which is well above the average reported intakes for UK and European children. In the main analyses, maternal BMI, TV-viewing duration, unhealthy snacking, and fruit and vegetable intakes were incorporated as time-varying factors.

Statistics

Descriptive Analysis
The characteristics of participants were summarised overall and according to categories of sleep duration for South Asian and White children separately. Trend tests and chi-square
tests explored differences in participant characteristics across sleep categories and across time-points. Chi-square, ANOVA and Kruskal-Wallis tests examined differences between ethnic groups and also compared the characteristics of included children against all those excluded from analyses. For included children, logistic regression was performed to investigate predictors of intermittent missing data.

**Main Analysis**
Sleep duration and each adiposity variable were regressed against follow-up time to evaluate the time trend for the whole sample, and for South Asian and White children separately. Models including follow-up time, time-squared and time-cubed were most appropriate to describe trends in adiposity. Mixed effects regression analyses were incorporated to efficiently analyse the repeated-measures data which were characterised by non-standard follow-up durations and missing values. This approach, which has previously been used to investigate bidirectional associations, allowed inclusion of up to four values of each exposure and outcome per child. The equations used to model associations (detailed in Supplementary Appendix 1) were mathematically comparable to a former publication, and initially involved modelling adiposity indicators as outcomes and sleep duration as a time-varying exposure, before inferring exposure and outcomes to model the reverse associations; each of the adiposity indicators were included in separate models. To assist comparisons of the effects of sleep duration on different adiposity measures, and vice versa, all exposure and outcome measures were standardised using means and standard deviations (SD) based on values from the mid-time point (24 months of age). The results represent the change in the outcome (in SDs) associated with a one SD change in the exposure. Our statistics showed significant interactions by ethnicity in both directions between sleep and total adiposity (p ≤ 0.041) hence all analyses have been stratified by ethnic group. There was no strong evidence for curvature of associations in either direction as identified by non-significant quadratic terms for exposure variables (p ≥ 0.13).

All models adhered to the same procedure for inclusion of confounders. After running crude models that included only baseline age and follow-up time (and time-squared and cubed when adiposity was the outcome), Model 1 was further adjusted for gender, SES, parity, gestational age, birth weight, birth season, maternal smoking in pregnancy, and maternal follow-up BMI. To elucidate the trajectory of associations over time, an interaction with follow-up time was added to Model 1, and the main effects of sleep duration on adiposity (and vice versa) at 6, 12 and 24 months of follow-up were calculated (Model 1a). In Model 2, TV-viewing duration, unhealthy snacking, and fruit and vegetable intake were added as potential confounders or mediators. Finally, a series of sensitivity analyses were applied to Model 2 that entailed further adjustment for breast feeding history, age introduced to solids, physical activity, and bedtime regularity, all of which had missing data. Maternal follow-up BMI was also exchanged for maternal early-pregnancy BMI as a covariate and total TV-viewing replaced by the hours of TV watched exclusively after 6pm. In final sensitivity analyses, adjustment for height in all models that involved adiposity indices not already indexed to stature or size (weight, waist circumference, and sum of skinfolds) was performed, fat mass and height were used to generate fat mass index (kg/m²) which was used as an alternative to %BF, and BMI was substituted in models for BMI z-score. Stata v13.1 (StataCorp., College Station, TX) was used for all analyses. Two tailed P-values of less than 0.05 were considered to be significant.

**RESULTS**

**Participant Characteristics**
The final analytical sample comprised 1,338 children (58% South Asian) who provided > 2400 observations. Complete data at all time-points were available for 399 participants and for most analyses the mean number of observations per child was 2.8. Table 1 provides a summary of demographic and birth characteristics overall and across sleep duration categories, stratified by ethnicity. Overall, South Asian mothers were on average older, had a lower early-pregnancy BMI, and birthed lighter babies than White mothers. A higher proportion of South Asian than White mothers were multiparous and gave birth in spring, whereas a higher proportion of White mothers gave birth in winter, occupied the least deprived SES category, and smoked in pregnancy. Table 2 summarises children’s behaviours (values for sleep duration, TV-viewing, unhealthy snacks, and fruit and vegetable intakes are averages from all time-points); overall there was no ethnic difference in sleep duration but South Asian children on average were breast fed for longer, introduced to solids at an older age, watched more TV after 6pm, consumed more daily portions of fruit and vegetables and more unhealthy snacks, and were less physically active compared to White children. The percentage of children who were reported to sleep < 11h and > 14h on average over the course of investigation was 7.0% and 12.5% in South Asian children and 5.3% and 8.0% in White children. In South Asians, there was a trend that longer sleep was associated with having a younger mother (Table 1), and as shown in Table 2 also shorter breast feeding duration, less TV-viewing, and more fruit and vegetables. In White children, longer sleep was associated with watching less TV after 6pm and a smaller proportion of winter births (Table 1). In both ethnic groups the proportion of children with regular bedtimes was highest in the longest reported sleep duration category (Table 2).

Table 3 summarises the repeated measures data at each discrete time-point. Parent reported sleep duration declined with age in both ethnic groups; at the 36 month time-point South Asian children were reported to sleep significantly more than White children. There were significant age-related increases in height, weight, fat mass and waist circumference, and significant trends of a decline in all other child adiposity measures. South Asian children were taller and consistently less adipose at all ages compared to White children. For time-varying covariates, TV-viewing duration (in total and exclusively after 6pm) and intake of unhealthy snacks increased with age in both ethnic groups, and in South Asians fruit and vegetable intake declined and maternal BMI increased. As per the mean overall data in Table 2, South Asian children were reported to consistently watch more TV, consume more unhealthy snacks and fruit and vegetables than White children.
Missing data comparisons revealed that a greater proportion of excluded children were classified as most deprived (22.4 vs. 15.8%) and were born to a mother that smoked in pregnancy (21.5 vs. 14.6%). Fewer excluded children had regular bedtimes (55.0 vs. 69.1%). With these exceptions, there were no other significant differences in any variables, at any time-point, for the difference between ethnic groups (chi-square, ANOVA or Kruskal-Wallis test). *P ≤ 0.05 for trend in the variable of interest across sleep categories (regression, skewed variables natural log transformed).

### Table 1—Participant demographic and birth characteristics according to ethnic group and categories of sleep duration.

| Sleep duration (h/day) | South Asian | White |
|------------------------|-------------|-------|
| Overall               |             |       |
| 11 to < 12            |             |       |
| (N = 159)             |             |       |
| 12 to < 13            |             |       |
| (N = 274)             |             |       |
| 13 to < 14            |             |       |
| (N = 192)             |             |       |
| > 14                   |             |       |
| (N = 97)              |             |       |

**Gender (N (%)) boys**

| South Asian | N       | Overall | < 11 (N = 54) | 11 to < 12 (N = 159) | 12 to < 13 (N = 274) | 13 to < 14 (N = 192) | > 14 (N = 97) |
|-------------|---------|---------|---------------|----------------------|----------------------|----------------------|---------------|
|             | 776     | 389 (50.1) | 33 (61.1) | 71 (44.7) | 147 (53.7) | 91 (47.0) | 45 (46.4) |

**Socioeconomic status (N (%))**

| South Asian | N       | Least deprived | Moderately deprived | Most deprived | Maternal pregnancy age (y) | Smoked in pregnancy (N (%)) | Previous births (N (%)) multiparous | Birth season (N (%)) |
|-------------|---------|----------------|---------------------|---------------|---------------------------|-----------------------------|-------------------------------|---------------------|
|             | 776     | 227 (29.3) | 452 (58.3) | 97 (12.5) | 776 | 27 (3.5) | 776 | 531 (68.4) |
|             | 389 (50.1) | 14 (25.9) | 31 (57.4) | 9 (16.7) | 776 | 27.6 ± 5.2 | 776 | 37 (68.5) |
|             | 33 (61.1) | 50 (31.5) | 81 (50.9) | 28 (17.6) | 776 | 27.8 ± 5.9 | 776 | 105 (66.0) |
|             | 71 (44.7) | 165 (60.2) | 115 (59.9) | 24 (8.8) | 776 | 28.3 ± 5.4 | 776 | 193 (70.4) |
|             | 147 (53.7) | 115 (59.9) | 115 (59.9) | 23 (12.0) | 776 | 27.8 ± 5.5 | 776 | 123 (64.1) |
|             | 91 (47.0) | 115 (59.9) | 115 (59.9) | 23 (12.0) | 776 | 26.8 ± 4.6 | 776 | 73 (75.3) |
|             | 45 (46.4) | 60 (61.9) | 60 (61.9) | 13 (13.4) | 776 | 27.1 ± 4.6 | 776 |             |

**White**

| White | N       | Overall | < 11 (N = 30) | 11 to < 12 (N = 112) | 12 to < 13 (N = 250) | 13 to < 14 (N = 125) | > 14 (N = 45) |
|-------|---------|---------|---------------|----------------------|----------------------|----------------------|---------------|
|       | 562     | 265 (47.2) | 14 (46.7) | 53 (47.3) | 117 (46.8) | 57 (45.6) | 24 (53.3) |

**Socioeconomic status (N (%))**

| White     | N       | Least deprived | Moderately deprived | Most deprived | Maternal pregnancy age (y) | Smoked in pregnancy (N (%)) | Previous births (N (%)) multiparous | Birth season (N (%)) |
|-----------|---------|----------------|---------------------|---------------|---------------------------|-----------------------------|-------------------------------|---------------------|
|           | 562     | 279 (49.6) | 168 (29.9) | 115 (20.5) | 562 | 26.5 ± 6.0 | 562 | 289 (51.4) |
|           |         | 11 (36.7) | 9 (30.0) | 10 (33.3) | 562 | 26.6 ± 6.2 | 562 | 13 (43.3) |
|           |         | 53 (47.3) | 36 (32.1) | 23 (20.5) | 562 | 25.9 ± 5.7 | 562 | 56 (50.0) |
|           |         | 134 (53.6) | 73 (29.2) | 23 (17.2) | 562 | 26.9 ± 5.8 | 562 | 128 (51.2) |
|           |         | 63 (50.4) | 33 (26.4) | 29 (23.2) | 562 | 26.4 ± 6.4 | 562 | 71 (56.8) |
|           |         | 18 (40.0) | 17 (37.8) | 10 (22.2) | 562 | 25.9 ± 7.3 | 562 | 21 (46.7) |

**South Asian ethnicity includes Pakistani (n = 688), Indian (n = 60), and Bangladeshi (n = 28); White ethnicity includes British (n = 535) and Other White (n = 27). Socioeconomic status groups correspond with Fairley et al.38 as follows: Least deprived (least socioeconomically deprived and most educated + employed, not materially deprived); Moderately deprived (employed, no access to money + benefits and not materially deprived); Most deprived (most economically deprived). For continuous variables, values are mean ± standard deviation or median (interquartile range) given skewness. †P ≤ 0.05, †††P ≤ 0.001 for the difference between ethnic groups (chi-square, ANOVA or Kruskal-Wallis test). *P ≤ 0.05 for trend in the variable of interest across sleep categories (regression, skewed variables natural log transformed).
between children included in the analyses (n = 1338) and those that were excluded (n = 397) from the original sample. With regards to children who were included, the only predictors of missing data were age and birth season; at each discreet time-point older children and children born in summer/autumn were less likely to have missing data.

**Mixed Effects Regression Between Sleep Duration (Exposure) and Adiposity as Outcomes**

Table 4 shows estimated associations from the mixed effects models with sleep duration modelled as the exposure and adiposity indices as outcomes. In South Asian children, sleep duration was inversely and independently associated with all measures of total adiposity except the sum of skinfolds (Model 1). Of the significant associations, standardised β-coefficients ranged from -0.024 (95% confidence interval (CI): -0.047, -0.0014) for weight to -0.031 (-0.062, -0.0013) for BMI. For weight and waist circumference the interaction between sleep duration and follow-up time was statistically significant, and the interaction approached statistical significance for BMI and %BF (p ≤ 0.089), suggesting that the inverse association between sleep duration and adiposity strengthened over time in South Asians. For example, the main effect (β (95% CI)) of sleep duration on waist circumference at 12 months was −0.028 (−0.064, 0.0081), and −0.070 (−0.14, −0.0038) at 24 months follow-up. This corresponded to a 0.26 (0.014, 0.52) cm reduced waist circumference with 1.4h more sleep at 24 months follow-up. The main effect of sleep duration on %BF was -0.069 (-0.12, -0.0017) at 24 months of follow-up, which corresponded to reduced %BF by 0.22 (0.054, 0.38) units for the same amount (1.4 h) of sleep. The overall effect of sleep duration on total adiposity indices was robust to further statistical adjustment indicating independence of associations (Model 2). With regards to White children, there were no significant associations between sleep duration and body mass index (BMI) or waist circumference.
Table 3—Participant characteristics at each measurement time-point according to ethnic group.

| South Asian | 12 months (baseline) | 18 months | 24 months | 36 months |
|-------------|----------------------|-----------|-----------|-----------|
|             | N        | N         | N         | N         |
| Age (months)| 682      | 12.7 (1.2)| 670       | 18.3 (1.2)| 648       | 25.0 (1.2)| 637       | 36.9 (1.1) |
| Sleep duration (h/day) | 679      | 13.0 ± 1.9| 670       | 12.6 ± 1.6| 646       | 12.5 ± 1.4| 637       | 11.9 ± 1.2†††,** |
| TV-viewing (h/day) | | | | | | | | |
| After 6pm   | 681      | 0 (0.5)†††| 668       | 0.1 (0.5)†| 648       | 0.5 (0.8)††| 636       | 0.5 (1.5)†††,*** |
| Total       | 681      | 0.5 (0.6)††| 668       | 1.0 (1.5)| 648       | 1.5 (2.1)†††| 636       | 2.0 (2.5)†††,*** |
| Unhealthy snacks (N, weekly) | 682      | 7 (9)     | 670       | 10 (11.5)| 648       | 12.5 (15.5)†††| 637       | 18 (21.5)†††,*** |
| Fruit & veg (daily portions) | 682      | 5.1 ± 2.6†††| 670       | 5.5 ± 2.4†††| 647       | 3.6 ± 2.0†††| 637       | 5.1 ± 3.0†††,** |
| Maternal BMI (kg/m²) | 658      | 25.8 (7.1)| 645       | 25.4 (6.9)| 604       | 25.8 (7.0)| 576       | 26.5 (6.8)*** |
| Weight (kg) | 653      | 9.7 ± 1.3††| 639       | 11.0 ± 1.5| 590       | 12.4 ± 1.7| 591       | 14.8 ± 2.2*** |
| Height (cm) | 647      | 76.2 ± 3.6†††| 604       | 82.4 ± 3.7†| 446       | 87.0 ± 3.6†††| 524       | 95.9 ± 4.1†††,*** |
| BMI (kg/m²) | 639      | 16.6 ± 1.8†††| 596       | 16.1 ± 1.6†††| 441       | 16.4 ± 1.6†††| 522       | 16.1 ± 1.6†††,*** |
| BMI z-score (kg/m²) | 639      | -0.74 ± 1.4†††| 596       | -0.71 ± 1.3†††| 441       | 0.17 ± 1.1†††| 522       | -0.013 ± 1.2†††,*** |
| Fat mass (kg) | 639      | 2.2 ± 0.5†††| 596       | 2.4 ± 0.6†††| 441       | 2.7 ± 0.7 | 522       | 3.2 ± 1.0*** |
| Fat mass index (kg/m²) | 639      | 3.8 ± 0.9†††| 596       | 3.5 ± 0.8†††| 441       | 3.6 ± 0.8†††| 522       | 3.4 ± 0.9†††,*** |
| Percent body fat | 639      | 22.8 ± 2.8†††| 596       | 21.8 ± 2.8†††| 441       | 21.4 ± 3.2†††| 522       | 21.0 ± 3.4†††,*** |
| Waist circumference (cm) | 572      | 43.4 ± 3.1†††| 529       | 44.7 ± 3.3†††| 400       | 47.7 ± 3.7†††| 484       | 49.9 ± 4.1†††,*** |
| Sum of skinfolds (mm) | 475      | 36.6 (11.2)†††| 430       | 33.4 (8.5)†††| 241       | 31.8 (8.8) | 305       | 28.0 (9.9)†††,*** |

| White | 12 months (baseline) | 18 months | 24 months | 36 months |
|-------|----------------------|-----------|-----------|-----------|
|       | N        | N         | N         | N         |
| Age (months)| 483      | 12.6 (1.5)| 478       | 18.5 (1.4)| 445       | 25.1 (1.3)| 454       | 36.7 (0.89) |
| Sleep duration (h/day) | 481      | 12.9 ± 1.4| 477       | 12.7 ± 1.3| 438       | 12.3 ± 1.4| 454       | 11.7 ± 1.2*** |
| TV-viewing (h/day) | | | | | | | | |
| After 6pm   | 483      | 0 (0.5)†| 477       | 0 (0.5)†| 445       | 0.1 (0.5)†| 454       | 0.4 (0.5)*** |
| Total       | 483      | 0.5 (1.0)†| 477       | 0.9 (1.0)| 445       | 1.0 (1.5)| 454       | 1.5 (1.4)*** |
| Unhealthy snacks (N, weekly) | 483      | 7 (8)    | 478       | 10 (8.5)| 445       | 10 (9.5)| 454       | 13 (12)*** |
| Fruit & veg (daily portions) | 483      | 4.3 ± 2.4 | 478       | 4.6 ± 2.2| 445       | 4.9 ± 2.2| 454       | 4.5 ± 2.6 |
| Maternal BMI (kg/m²) | 466      | 25.6 (9.0)| 451       | 25.5 (9.1)| 406       | 26.1 (9.0)| 365       | 25.5 (7.7) |
| Weight (kg) | 473      | 9.9 ± 1.2| 458       | 11.2 ± 1.3| 423       | 12.5 ± 1.6| 425       | 14.8 ± 1.9*** |
| Height (cm) | 465      | 75.6 ± 3.5| 446       | 82.0 ± 3.4| 364       | 86.1 ± 3.5| 392       | 94.6 ± 4.1*** |
| BMI (kg/m²) | 463      | 17.3 ± 1.5| 440       | 16.6 ± 1.4| 360       | 16.8 ± 1.5| 387       | 16.5 ± 1.3*** |
| BMI z-score (kg/m²) | 463      | -0.15 ± 1.1| 440       | -0.30 ± 1.0| 360       | -0.11 ± 1.2| 387       | 0.33 ± 0.9*** |
| Fat mass (kg) | 463      | 2.4 ± 0.5| 440       | 2.5 ± 0.5| 360       | 2.8 ± 0.6| 387       | 3.2 ± 0.7*** |
| Fat mass index (kg/m²) | 463      | 4.2 ± 0.7| 440       | 3.8 ± 0.7| 360       | 3.7 ± 0.8| 387       | 3.6 ± 0.7*** |
| Percent body fat | 463      | 24.0 ± 2.3| 440       | 22.5 ± 2.4| 360       | 22.0 ± 3.0| 387       | 21.7 ± 2.8*** |
| Waist circumference (cm) | 413      | 44.1 ± 3.0| 391       | 46.0 ± 3.3| 330       | 48.2 ± 3.2| 361       | 50.7 ± 3.4*** |
| Sum of skinfolds (mm) | 296      | 41.4 (13.8)| 306       | 36.0 (9.4)| 224       | 31.8 (8.3)| 223       | 31.8 (8.4)*** |

South Asian ethnicity includes Pakistani, Indian, and Bangladeshi; White ethnicity includes British and Other White; Values are mean ± standard deviation or median (interquartile range) given skewness. †P ≤ 0.05, ††P ≤ 0.01, †††P ≤ 0.001 for the difference between ethnic groups at each time-point (ANOVA or Kruskal-Wallis test). **P ≤ 0.01, ***P ≤ 0.001 for trend in the variable of interest across time-points (regression, skewed variables natural log transformed). BMI, Body mass index. BMI z-scores based on UK reference data from Cole et al. 1995.
and adiposity regardless of the level of adjustment, and no significant interactions between sleep duration and follow-up time. All of the presented results were consistent with crude models and were unchanged in sensitivity analyses.

**Mixed Effects Regression Between Adiposity (Exposures) and Sleep Duration as the Outcome**

When sleep duration was modeled as the outcome, inverse independent associations were consistently observed in South Asian children for weight, BMI and %BF (Table 5). The overall effects of adiposity on sleep duration were consistent between Models 1 and 2, and associations were approximately two- to three-fold greater in magnitude compared with reciprocal relations when sleep duration was the exposure. Of the significant associations, adjusted standardized $\beta$-coefficients ranged from $-0.064 (-0.12, -0.0057)$ for weight to $-0.10 (-0.16, -0.028)$ for %BF (Model 2). On the original scales, these associations translated to reduced sleep by $5.4 (0.48, 10.1) \text{ min/d}$ and $8.4 (2.4, 13.4) \text{ min/d}$ for every additional $1.7 \text{ kg body weight}$ and $3.2 \text{ %BF}$, respectively. Interactions between adiposity variables and follow-up time were not statistically significant (Model 2). In South Asian children, no associations were apparent for waist circumference or for the sum of skinfolds, and again no significant associations were observed in White children. All of the presented results were consistent with crude models and sensitivity analyses.

**DISCUSSION**

This study incorporated repeated data spanning approximately 12 to 36 months of age to investigate associations between parent reported sleep duration and measured adiposity in South Asian and White children from a deprived location. We also evaluated the extent to which these associations changed over time and bidirectionality of associations. We found no
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**Table 5**—Associations of total and abdominal adiposity (exposures) with sleep duration (outcome) from mixed effects models using data at all time-points.

| Outcome Exposure | N (Observations) | Overall main effect (Model 1) | Interaction effect with follow-up time (Model 1a) | Main effect at 6m follow-up (Model 1a) | Main effect at 12m follow-up (Model 1a) | Main effect at 24m follow-up (Model 1a) | Overall main effect (Model 2) |
|------------------|-----------------|-----------------------------|-----------------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|-------------------------------|
| South Asian      |                 |                             |                                               |                                        |                                        |                                        |                               |
| Sleep duration Weight | 775 (2406)     | -0.067 (-0.13; -0.0089)*    | 0.0011 (-0.0020; 0.0043)                      | -0.078 (-0.14; -0.012)*               | -0.071 (-0.13; -0.011)*               | -0.057 (-0.12; 0.0076)              | -0.064 (-0.12; -0.0057)*        |
|                  | BMI             | -0.072 (-0.13; -0.018)**    | -0.00070 (-0.0052; 0.0038)                    | -0.070 (-0.13; -0.015)*               | -0.074 (-0.13; -0.018)**              | -0.083 (-0.17; 0.0062)              | -0.067 (-0.12; -0.013)*        |
|                  | %BF             | -0.097 (-0.16; -0.031)**    | -0.00092 (-0.0057; 0.0039)                    | -0.094 (-0.16; -0.024)*               | -0.099 (-0.17; -0.032)*               | -0.11 (-0.20; -0.016)*             | -0.10 (-0.16; -0.028)**        |
|                  | WC              | -0.027 (-0.087; 0.034)      | 0.00020 (-0.0043; 0.0047)                     | -0.028 (-0.093; 0.037)               | -0.026 (-0.087; 0.035)               | -0.024 (-0.11; 0.060)              | 0.0021 (-0.082; 0.039)         |
|                  | SSF             | -0.022 (-0.081; 0.038)      | -0.0042 (-0.0096; 0.0012)                    | -0.017 (-0.077; 0.043)               | -0.042 (-0.11; 0.023)                | -0.092 (-0.20; 0.017)              | -0.018 (-0.077; 0.041)         |
| White            |                 |                             |                                               |                                        |                                        |                                        |                               |
| Sleep duration Weight | 562 (1654)     | 0.030 (-0.041; 0.10)        | -0.0021 (-0.0065; 0.0014)                     | 0.047 (-0.029; 0.12)                 | 0.035 (-0.036; 0.11)                 | 0.0099 (-0.068; 0.088)             | 0.031 (-0.040; 0.10)           |
|                  | BMI             | 0.0046 (-0.056; 0.065)      | -0.0029 (-0.0082; 0.0023)                     | 0.010 (-0.051; 0.071)                | -0.0075 (-0.072; 0.057)              | -0.043 (-0.15; 0.062)              | 0.0047 (-0.056; 0.065)         |
|                  | %BF             | 0.0060 (-0.070; 0.081)      | -0.0030 (-0.0084; 0.0023)                     | 0.017 (-0.061; 0.095)                | -0.0013 (-0.078; 0.075)              | -0.038 (-0.15; 0.070)              | 0.0079 (-0.068; 0.084)         |
|                  | WC              | 0.013 (-0.045; 0.071)       | -0.00060 (-0.0048; 0.0036)                    | 0.015 (-0.045; 0.075)               | 0.012 (-0.047; 0.071)                | 0.0046 (-0.080; 0.089)             | 0.014 (-0.045; 0.072)          |
|                  | SSF             | 0.0034 (-0.048; 0.055)      | 0.0020 (-0.0038; 0.0078)                      | 0.0058 (-0.046; 0.058)               | 0.018 (-0.049; 0.084)                | 0.042 (-0.081; 0.16)              | 0.0043 (-0.047; 0.056)         |

Abbreviations: %BF, Percentage body fat; BMI, Body mass index; WC, Waist circumference; SSF, Sum of skinfolds (triceps, subscapular and thigh). South Asian ethnicity includes Pakistani, Indian, and Bangladeshi; White ethnicity includes British and Other White. Results are standardised regression coefficients (95% confidence interval) and should be interpreted as the change in outcome (in SD units) per 1 SD higher value of the exposure. Each adiposity parameter was included in a separate model. Model 1 is adjusted for baseline age and follow-up time, gender, socio-economic status, parity, gestational age, birth weight, season of birth, maternal pregnancy age, maternal smoking in pregnancy, and maternal follow-up BMI. Model 1a: Model 1 with an interaction term between adiposity and follow-up time. Model 2: As model 1 but further adjusted for TV-viewing duration, unhealthy snacking, and fruit and vegetable intake. *P ≤ 0.05, **P ≤ 0.01. Significant results are highlighted bold.

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Significant associations in White children. However, there was evidence of an independent bidirectional relation between sleep duration and adiposity in South Asian children.

**Sleep Duration as the Exposure and Adiposity as Outcomes**

A recent meta-analysis concluded that for every additional hour of daily sleep the annual BMI gain in children and adolescents was lower by 0.05 (0.01, 0.09) kg/m², with no appreciable effect modification by age. Our analysis yielded equally modest magnitudes of association: per 1.4 h/day of additional reported sleep the overall main effect in South Asian children was lower BMI by 0.05 (0.0021, 0.10) kg/m². We did find, however, that the association strengthened over time, and at 24 months of follow-up the same amount of parent-reported sleep was associated with lower BMI by 0.13 (0.027, 0.24) kg/m². The observation that follow-up time modified the association between sleep duration and adiposity may reflect a lag or cumulative effect of short sleep on adiposity.

Few studies have investigated outcomes other than BMI, but similar to this study an investigation of Danish children failed to find an association between infant sleep duration (at 9 and 18 months) and the sum of skinfolds at 36 months. In contrast to our results, however, which may in part be explained by skinfolds representing a different measure of adiposity to height-for-weight indices and circumferences, that small study also reported null associations for fat mass and %BF. In another study, German children who slept more at 18 and 24 months exhibited progressively lower fat mass index levels up to age 7 years compared to children that slept less. Likewise, in a sample of predominantly White Americans, greater sleep curtailment from age 6 months to 7 years was associated with higher total and truncal fat mass index, waist and hip circumference. The current study is the first to be performed in a deprived,
Adiposity as Exposures and Sleep Duration as the Outcome
To our knowledge, just two studies, both conducted with Australian children, have investigated the influence of adiposity on sleep duration. The first reported that BMI measured before 18 months of age was not associated with sleep duration at age 2-3y; an association of sleep predicting BMI was also not found. The same study reported null results in both directions for preschool children from the same cohort (aged 4-5y at baseline and 6-7y at follow-up). Subsequent investigation of the same pre-schoolers found no evidence for an association between baseline BMI and sleep duration at 8-9y in the whole sample, but a significant inverse association was observed when analyses were restricted to children from disadvantaged homes. This supports results from our study, but we uniquely found that indicators of adiposity were inversely associated with reported sleep duration in South Asian children from a deprived location but not White children; for every additional 3.2 %BF sleep was reduced by 8.4 (2.4, 13.4) min/d in South Asians. This may seem clinically insignificant, but concerns have been raised regarding a global 0.75 min/d annual decline in childhood sleep over the 20th century, which lower adiposity could seemingly help to counteract. Of note is that the relative magnitude of association between adiposity and sleep duration was greater than the reciprocal association. However, we issue a note of caution before interpreting this to mean that adiposity exerts a greater influence on sleep duration than vice versa. Habitual behaviours like sleep are often subject to greater measurement imprecision than anthropometric data, and this could explain the greater magnitudes of association (and wider CIs) when sleep was the outcome as opposed to the exposure. Despite this measurement conundrum, we have highlighted for the first time that adiposity is both a potential determinant of decreased sleep and a consequence in early childhood.

There are many plausible biological and behavioural explanations to account for the observed inverse associations between sleep duration and adiposity, they have been described comprehensively by others. It is noteworthy that the associations reported in this paper were independent of TV-viewing, diet, and physical activity levels, all of which have been proposed as mediating factors. The associations between adiposity and curtailed sleep may be mediated by poorer general health and physiological disorders such as sleep apnoea. But the puzzling question emerging from our results is why were associations observed in South Asian but not White children? Reported sleep durations were largely similar between ethnic groups, and for this reason our first suggestion is that there may be ethnic differences in sleep requirement, with South Asians potentially having a greater sleep need than White children. Ethnic differences in the prevalence of paediatric sleep apnoea have also been reported, so it may be that South Asian children are more susceptible to obesity-driven sleep apnoea, but this has not been investigated. Another possibility is confounding or residual mediating effects, maybe by factors that are associated with sleep and adiposity in South Asians more so than in Whites, and which we either controlled for inadequately (e.g. parent-reported physical activity) or were unable to control for (e.g. sleep pattern or quality). With regard sleeping patterns, our diary data from a sub-sample highlighted that South Asian children had later bedtimes (median (interquartile range): 9:25pm (80 min) vs. 7:46pm (55 min)) and were later to rise (8:17am (85min) vs. 7:10am (55 min)) than White children. Others have similarly reported later sleeping in non-White children which is a pattern that seems to be associated with higher adiposity. There may have also been ethnic differences in the proportion of total sleep time accumulated overnight. We were unable to differentiate between daytime and nocturnal sleep from the questionnaire reports, but in line with observations that non-White children nap less frequently, our diary data indicated that South Asian children slept more during the day (1.5 (2.0) h/day vs. 1.0 (1.3) h/day in White children). It has been suggested that daytime sleep is an inadequate substitute for nocturnal sleep, and therefore further investigation is needed to establish if these types of sleeping pattern may have confounded our results. Another suggested possibility is differential bias in parent-reported sleep. Co-sleeping is more prevalent in South Asian families meaning that South Asian parents may have reported children’s sleep with greater accuracy. 

Strengths and Weaknesses
This investigation benefited from comprehensive data collection in an ethnically diverse and economically deprived cohort that was followed from birth to 36 months with relatively low attrition. This is an important population to study to improve our understanding of health inequalities and in particular to address the high risk of obesity and cardiometabolic disease in adult South Asian populations to which rapid infant growth might contribute. Rapid post-natal growth has been positively associated with child health in low income countries, and particularly in preterm and small for gestational age infants is needed to achieve appropriate developmental goals, but only 5% of our UK-resident South Asian children were born pre-term (< 37 weeks). We accept that proxy reported sleep estimates are subject to measurement error and bias, but objective methods that have been successfully used in older children suffer in this age group from low specificity in identifying night waking. As such, diaries may currently be the optimal method for assessing sleep duration in young children, and reassuringly our questionnaire data were correlated with parent-reported diaries that accounted for this paper were independent of TV-viewing, diet, and physical activity levels, all of which have been proposed as mediating factors. The associations between adiposity and curtailed sleep may be mediated by poorer general health and physiological disorders such as sleep apnoea. But the puzzling question emerging from our results is why were associations observed in South Asian but not White children? Reported sleep durations were largely similar between ethnic groups, and for this reason our first suggestion is that there may be ethnic differences in sleep requirement, with South Asians potentially having a greater sleep need than White children. Ethnic differences in the prevalence of paediatric sleep apnoea have also been reported, so it may be that South Asian children are more susceptible to obesity-driven sleep apnoea, but this has not been investigated. Another possibility is confounding or residual mediating effects, maybe by factors that are associated with sleep and adiposity in South Asians more so than in Whites, and which we either controlled for inadequately (e.g. parent-reported physical activity) or were unable to control for (e.g. sleep pattern or quality). With regard sleeping patterns, our diary data from a sub-sample highlighted that South Asian children had later bedtimes (median (interquartile range): 9:25pm (80 min) vs. 7:46pm (55 min)) and were later to rise (8:17am (85min) vs. 7:10am (55 min)) than White children. Others have similarly reported later sleeping in non-White children which is a pattern that seems to be associated with higher adiposity. There may have also been ethnic differences in the proportion of total sleep time accumulated overnight. We were unable to differentiate between daytime and nocturnal sleep from the questionnaire reports, but in line with observations that non-White children nap less frequently, our diary data indicated that South Asian children slept more during the day (1.5 (2.0) h/day vs. 1.0 (1.3) h/day in White children). It has been suggested that daytime sleep is an inadequate substitute for nocturnal sleep, and therefore further investigation is needed to establish if these types of sleeping pattern may have confounded our results. Another suggested possibility is differential bias in parent-reported sleep. Co-sleeping is more prevalent in South Asian families meaning that South Asian parents may have reported children’s sleep with greater accuracy. 

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for both daytime napping and broken sleep. We advantageously investigated multiple indicators of total and abdominal adiposity, and although alternative lab-based imaging methods (e.g. DXA) may have provided more accurate measurement of adiposity, a previous study showed consistency in associations regardless of whether DXA-derived outcomes or more feasible anthropometric indices were used. Inevitably there were missing data, which were also found to be patterned by birth season, but our results were unchanged whether or not they were adjusted for this factor. In fact, our results were robust to adjustment for diverse covariates including dietary components and bedtime regularity, which are uncommonly controlled for. It is possible, nevertheless, that confounding still existed in models due to measurement inaccuracy and factors that we were unable to include (e.g. gestational weight gain, sleep patterns and quality). To strengthen claims regarding causality, analyses which manipulate sub-selections of exposure and outcome to investigate early change in exposure with late change in outcome are needed.

CONCLUSION
Our results provide evidence for bidirectional associations between sleep duration and adiposity in young children, specifically young South Asian children living in the UK. Further investigations are needed to determine whether cyclical episodes of shortened sleep and adiposity gain may cast negative health effects upon South Asian children from an early age.

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SUPPLEMENTARY MATERIAL
Supplementary Appendix 1 is available at SLEEP online.

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AUTHORS’ CONTRIBUTIONS
PIC conceived this investigation, planned and executed analyses, and wrote the manuscript; GS assisted data management. JWr, SB, RRCM and JWe designed and implemented the cohort. All authors critically revised the manuscript for intellectual content, helped interpret study findings, and read and approved the final manuscript.
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CONFLICT OF INTEREST
The authors declare no conflict of interest.