The effects of sun intensity during pregnancy and in the first 12 months of life on childhood obesity

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Abstract

Abstract: Obesity not only leads to immense medical costs associated with treating obesity-related illness but is also associated with lower employment prospects and earnings. This study shows that sunshine-induced vitamin D may have a preventive effect on obesity for children. It investigates the relation between sun intensity from pregnancy until infancy on obesity at age six, using population data of more than 600,000 children. Our findings show that the effects of sun intensity on subsequent obesity are concentrated in the first six months of life: 100 hours of additional sunshine over this period reduce overweight by 1.1 percent and severe obesity by 6.2 percent. We offer two main explanations for this pattern. First, infants' vitamin D levels are particularly sensitive to sunshine in the first six months of life, when lactation is highest. Second, the first six months of life are a sensitive period for later obesity, as this is the period when infants rapidly gain weight and adipose tissue develops.

JEL-Classification: I18, I12

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1. Introduction

Childhood obesity in the U.S. has risen from 5 percent to 10.4 percent between 1974 to 2000 among two-to-five-year-olds and further increased afterwards (Cawley, 2015). Other Western countries show similar trends (e.g., Zellner et al., 2007 for Germany; Black et al., 2018 for Australia). It causes large costs, estimated at $14.1 billion per year in the US through higher medical services utilization of the affected children alone (summarized in Cawley, 2010). Childhood obesity also strongly correlates with later obesity: about a third of obese preschool children, and about half of obese school-age children, become obese adults (Serdula et al., 1993). Adulthood obesity not only leads to immense medical costs associated with treating obesity-related illness, amounting to $147 billion dollars per year in the US (Finkelstein et al., 2009), but is also associated with lower employment prospects and earnings, in particular for women (e.g., Averett, 2014). The long-term societal and individual costs of childhood obesity therefore greatly exceed its direct medical costs and make it vitally important to better understand its causes and ways to prevent it.

In this paper, we seek to understand the effects of vitamin D on childhood obesity. While an existing literature has explored this relationship, it has been challenging to disentangle the impact of vitamin D exposure from that of other socio-economic factors. We shed light on this issue by exploiting plausibly exogenous variation in vitamin D levels through sunlight exposure—the primary source of vitamin D for children and adults (e.g., Hossein-Nezhad and Holick, 2013). There is clear evidence of correlations between individuals' exposure to sunlight and vitamin D levels on the one hand (e.g., Gorman et al., 2017), and between vitamin D levels and obesity in adults and children on the other hand (Pereira-Santos et al., 2015, Turer et al., 2013, Wortsman et. al., 2000).[1] The direction of causality, however, is unclear (Vanlint, 2013). Do higher levels of vitamin D levels reduce the risk of obesity? Or do obese individuals spend less time in the sun, leading to lower vitamin D levels in their bodies? Our analysis is the first large-scale study that establishes a causal link from children's early sunlight exposure that induces vitamin D production to subsequent childhood obesity. Although we do not directly measure the impact of sunshine on individual vitamin D production, we consider vitamin D the most plausible channel through which sunshine affects obesity.

Two recent studies adopt a similar design as us and establish a causal link between increased sunshine exposure during pregnancy and birth weight for black (but not white) mothers who are particularly likely to be vitamin D deficient on the one hand (Trudeau et al., 2016), and between increased sunshine exposure during pregnancy and the risk of asthma later in life on the other hand (Wernerfelt et al., 2017). Our work complements these papers by considering an additional outcome—adiposity at age six—and by pinpointing the exact period – pregnancy versus the first three, six, twelve or later months of life – when sunlight exposure is most relevant for childhood obesity.

Our empirical analysis is based on data from compulsory school entry examinations and health screenings undertaken by pediatricians and cover all children prior to school entry at age six in 44 German districts over nearly two decades. We combine this data source with information on daily sun hours at the district level. To obtain the causal effects of sun intensity on childhood obesity during pregnancy and during different stages of a child's life, our research design holds constant important confounding factors such as district of birth, which may be correlated with children's health through for example differences in lifestyles or diets (e.g.,

[1] According to the meta-study by Pereira-Santos et al. (2015), obese and overweight individuals show a 35% and 24% higher risk of vitamin D deficiency than average weight individuals.

Sofi et al., 2014, Tucker and Gilliland, 2007); year of birth, which may be correlated with children's health through for example business cycle effects (e.g., Dehejia and Lleras-Muney, 2004); and month of birth which the existing literature has shown to correlate with demographic characteristics (e.g., Currie and Schwandt, 2013) that are themselves correlated with obesity.

Our analysis shows that 100 hours more sunshine in the first six months after birth – which is equivalent to the increased sun intensity from a two-and-a-half-week-long holiday in winter to a destination where sunshine is similar to that in summer – reduces overweight at age six by 1.1 percent and severe obesity at age six by 6 percent. These estimates imply 1,119 fewer overweight and 420 fewer severely obese children per birth cohort (677,947 children were born in 2010 in Germany) per 100 additional sunshine hours in the first six months after birth. In contrast, increased sunshine hours in the second half of the child's first year and beyond have no detectable impact on overweight or severe obesity at age six. Increased sun intensity in the last trimester of pregnancy also tends to reduce the risk of subsequent adiposity, but this effect is smaller in magnitude than that of sun intensity in the first six months of life and statistically significant in only some specifications.

There are three main explanations for why the effects of sun intensity induced vitamin D production on subsequent obesity is concentrated in the first six months of life. First, the first six months of life coincide with the period when lactation is highest. In this period, the typical infant acquires vitamin D primarily through the ingestion of breast milk, which is likely to contain lower levels of vitamin D when sun intensity is low. As the child gets older, baby food – which is typically enriched with vitamin D (e.g., formulae or baby porridge) – becomes a more important part of the child's diet, making their vitamin D levels less sensitive to sun intensity. Second, vitamin D may directly reduce infants' weight and BMI in the first six months of life, as it affects lipogenesis, a metabolic process through which certain molecules are converted to body fat (Wood 2008; Abbas 2017). Since BMI in the first six months of life is strongly correlated with BMI later in life (e.g., Taveras et al., 2009; Baird et al., 2005; Roy et al., 2016), increased sun intensity in the first six months of life may directly lead to higher risk of obesity at age six. Third, the functions of the adipose tissue primarily develop in the first six months after birth. Vitamin D deficiency hinders this development, increasing the risk of obesity later in life (Ding et al., 2012). The second and third explanations suggest that the first six months of life are a sensitive period for subsequent obesity.

Our paper contributes to the literature on the causes of childhood obesity**.** Existing papers have focused on high calorie intake (e.g., Currie et al., 2010) and lack of physical activity (e.g., Kimm et al., 2005) as the two main causes of childhood obesity. Our paper adds an additional, so far unexplored, potential cause of childhood obesity, insufficient exposure to sunlight and the resulting vitamin D deficiency in pregnancy and early life. Even though the effect of sunshine in the first months of the child's life on later obesity is considerably weaker than that of dietary intake or physical exercise later in life, our findings suggest that vitamin D supplements for infants, due to their low production costs, may be a cost-effective way to reduce childhood obesity.

A small number of studies has directly investigated the effects of vitamin D supplements early in life on children's health outcomes later in life in randomized control trials.[2] Hazell et al. (2017) report some suggestive evidence that vitamin D supplements in infancy reduces fat mass and body fat at age 3. This study, however, is based on a small sample (132 children at

[2] For adults, studies are likewise scarce and inconclusive. While two double blind randomized control studies find that vitamin D supplementation enhanced weight loss (Mason et al., 2014) or lowered body fat mass (Salehpour et al., 2012) for specific subgroups, Soares et al. (2011), in a summary of the literature, conclude that "current evidence from RCTs did not consistently support the contention that calcium and vitamin D accelerated weight or fat loss in obesity".

baseline) and suffers from a large rate of attrition (only 66% of the 132 children participated in a follow-up at age three).

The randomized control study by Trilok-Kumar et al. (2015), which establishes a causal link between vitamin D supplements in infancy and height and weight at age 5, is based on a considerably larger sample (2079 infants at baseline), although follow-up attrition is high, too - only 912 children (43.8%) participated in a follow-up at age five. Our study provides several additional insights. First, while Trilok-Kumar et al. (2015) concentrate exclusively on infants with low birthweight, and in consequence oversamples children from disadvantaged families, we study the entire population of children. Second, while Trilok-Kumar et al. (2015) focus on BMI as an outcome and do not investigate the effects of vitamin D supplements along the BMI distribution, we also provide an analysis on adiposity and thus focus on the effects of sunshine exposure on the upper tails of the BMI distribution. And third, while their investigation is for India, a developing country where both malnutrition and obesity are of concern, our study takes place in Germany, a highly developed country where malnutrition is very rare but obesity is not. In consequence, the hypotheses in Trilok-Kumar et al. (2015) and our work are different. While Trilok-Kumar et al. (2015) conjecture that vitamin D helps children with low birthweight gaining weight, we instead hypothesize that sunshine-induced vitamin D reduces the risk that healthy children become overweight. Finally, in contrast to the study by Trilok-Kumor, our research design allows us to pinpoint the exact period when vitamin D matters for later obesity.

We further contribute to the small literature that establishes a link between sun intensity and health outcomes. Existing studies typically find that more sunlight is related to lower obesity (e.g., Gorman et al., 2017, for a review). In contrast to our work, these studies typically focus on the contemporaneous link between sunlight and obesity, rather than on the effects of sunlight during pregnancy and early life on obesity later in life. Moreover, these studies exploit variation in sunlight either across districts (using variation in sun intensity due to differences in latitude and altitude as e.g., Woolcott et al., 2014 or Voss et al., 2014) or across seasons (e.g., Dietz and Gortmaker, 1984 or Visscher and Seidell, 2004), and are thus likely to overstate the causal effect of sunlight on obesity that operates through raising vitamin D levels, as people are often more active and eat a healthier diet in more compared to less sunny areas or seasons, both of which are strong predictors of obesity (Sofi et al., 2014; Tucker and Gilliland, 2007). Our research design eliminates these confounding factors, by leveraging variation in sun intensity within districts and within seasons, across birth cohorts.

Overall, our findings highlight that increased sun intensity in the first six months of life may have a preventive impact on obesity, most likely through raising vitamin D levels. These findings have important public health implications, as vitamin D intake can be increased easily and at low cost through dietary supplements.

The remainder of the paper is organized as follows. In Section 2, we review the mechanisms through which increased sun intensity at various stages of a child's life may affect current and subsequent obesity by raising vitamin D levels, as discussed in the medical and biological literature. In Section 3, we describe the data sources used in the empirical analysis. In Section 4, we lay down the empirical strategy to identify the causal effects of sun intensity at different stages of a child's life on childhood obesity at age six. We report findings in Section 5 and conclude with a discussion of our findings in Section 6.

2. Sun Intensity, Vitamin D and Obesity

Several studies have documented a clear and robust correlation between vitamin D and obesity (Pereira-Santos et al., 2015, Turer et al., 2013, Wortsman et. al., 2000). The direction of causality is, however, unclear. On the one hand, obese individuals may simply be less active and spend less time outside and may thus be less exposed to sunshine than non-obese individuals, leading to lower vitamin levels in their body (Vimaleswaran et al., 2013; Tucker

& Gilliland, 2007). At the same time, obese individuals may consume a diet that includes fewer vitamin D-rich products, such as fish, avocados, or mushrooms (Hyppönen et al., 2007). On the other hand, vitamin D levels may have a causal effect on obesity, as adequate vitamin D intake may enhance weight loss and decrease body fat. The argument here is that vitamin D is produced on the skin and in the adipose tissue under the skin. This process starts only when the skin is exposed to sunlight. During this process of vitamin D creation, extra calcium flows into fat cells, thereby affecting lipogenesis, a metabolic process through which certain molecules are converted to body fat (Martini and Wood, 2006).

While this argument provides an explanation for why *current* vitamin D levels may causally affect *current* obesity risk, vitamin D deficiency in the first months of a child's life may have long-lasting effects on obesity once the child is older, as the first few months of life are considered a sensitive period for the development of subsequent obesity, for two reasons. First, the infant's weight more than doubles in the first six months and about triples in the first year of life (Butte et al., 2000). At the same time, rapid weight gain in the first three and six months of life is strongly associated with higher BMI later in life (e.g., Taveras et al., 2009, Baird et al., 2005, Roy et al., 2016). Second, a large proportion of the adipose tissue develops during this period (Poissonnet et al., 1988). The adipose tissue is a structure, like an organ, that has important functions in metabolism, particularly in storing and absorbing fat. Biological research suggests that vitamin D is essential for the tissue to sufficiently develop all its functions (Ding et al., 2012). If the adipose tissue has not developed its metabolism functions sufficiently well, it may store additional fat conditional on similar calorie intake, increasing the risk of obesity later in life.

A further explanation for why the effects of sun intensity on subsequent obesity are concentrated in the first six months of life is related to the idea that the infant's vitamin D levels are particularly sensitive to sunlight in exactly this period. The first six months after birth are the period in which lactation is highest. Around the world, mothers are strongly encouraged to exclusively breastfeed their child for six months and continue breastfeeding up to the age of two years or beyond (e.g., World Health Organization or the National Breastfeeding Commission for Germany). In Germany 76.7 percent of children born between 1986 and 2005 were breastfed, with an average nursing duration of 4.59 months of sole breastfeeding and 6.9 months of breastfeeding with complementary feeding (Lange et al., 2007). A newborn infant who is solely breastfed can acquire vitamin D through direct dietary supplementation, direct sun intensity, or ingestion of breast milk. In the U.S., only between 10% and 16% of breastfed infants receive direct vitamin D supplements, according to a survey with over 2,000 participants conducted between 2006 and 2008 (Taylor et al., 2010). Pediatric advice, such as that of the American Academy of Pediatrics, strongly advises against direct sun exposure of infants during the first six months of life (American Academy of Pediatrics, 1999). This leaves breast milk as the main plausible source of vitamin D. As maternal vitamin D supplementation during lactation leads to higher vitamin D levels in their children (Hollis et. al, 2015), it is likely that increased sun intensity also leads to higher maternal vitamin D levels that are then transferred to the child through breastfeeding. As the child gets older, baby food – which is typically enriched with vitamin D (e.g., formulae or baby porridge) – becomes a more important part of the child's diet, making her vitamin D levels less sensitive to sun intensity.

Similar to a breastfed infant, the vitamin D levels of a fetus are tied to those of its mother. Moreover, while adipose tissue primarily develops in the first six months of the child's life, this process starts during pregnancy (Poissonnet et al., 1988). Increased sun intensity during pregnancy, in particular during the last trimester, may therefore also lower the subsequent risk of adiposity. As vitamin D take-up is higher among pregnant women than among mothers who have just given birth (Aronsson et al., 2013), sun intensity during pregnancy may have a smaller impact on subsequent childhood obesity than sun intensity during the lactation period.

3. Data and Sample

Our study makes use of a unique feature of the German school system that requires all children to undergo compulsory school entry examinations prior to school entry at age six. Examinations are designed to assess children's school readiness and identify any developmental delays or health problems including child obesity. The 45-minute test is typically administered in a nearby elementary school in the child's municipality in the spring before August school entry. Government pediatricians conduct the test, which includes an interview with the child, a battery of motor skills and physical development tests, as well as the precise measurement of height and weight with scale and tape. In contrast to most datasets used by economists, which rely on parents' self-reports of their children's weight and height, an important advantage of our obesity measure is that it represents standardized assessments by health professionals. This is a major advantage as subjective statements by parents about their children's height and weight are prone to bias (e.g., Cullinan and Cawley, 2017, Weden et al., 2013).

Our school entry examinations data cover 16 birth cohorts (1986-2001) from 50 districts in three federal states in the North (Schleswig-Holstein), North-West (Lower Saxony), and East (Brandenburg) of Germany (see Appendix Figure B1). In addition to precise information on height and weight, we observe some background variables, such as the child's month and year of birth, district of residence, gender, and ethnicity. Additional socio-economic background variables, such as parental education and unemployment, are included only for the more recent 1998-2001 birth cohorts.

We supplement the school entrance examination data with information on the sunshine hours in each district in each month of each year. Our measure for sunshine hours comes from 21 of the 74 weather stations across Germany that collect information on hours of sunshine on a daily basis. To create our baseline measure, we first sum up daily hours of sunshine in each month, in each year, and for each weather station. We then identify all weather stations within a 50 kilometers (31 miles) radius from the center of the district (there are at most four such weather stations per district), leaving us with 44 districts which have a least one weather station within a radius of 50 kilometers. After restricting our sample to children who are older than 67 and younger than 81 months at the date of examination, and excluding children with implausible height and weight values, our main sample includes 666,258 children.[3]

Finally, we average sunshine hours per month and year over those stations, inversely weighted by distance. 16 of the 44 districts in our data are assigned the exact same set of weather stations as other districts, leaving us with 28 unique "weather station districts". For each child in our sample, we finally compute total sunshine hours, divided by 100, in seven three-month intervals, starting from the beginning of pregnancy to the end of the first year. Our results are robust to alternative cut-off rules (e.g., 50 miles rather than 50 kilometers) and alternative weighting schemes of weather stations (e.g., uniform weighting across weather stations); see Table 5.

A drawback of our data is that we only observe the district of residence at the time of the school entry examination, as opposed to the district during pregnancy and the first months of life. Evidence from the Sample of Integrated Labor Market Biographies (SIAB) and the German Socio-Economic Panel (GSOEP) suggests that mobility across districts is relatively small: at most 15% of first-time mothers reside in a different district when their child is six years old than during pregnancy (see Appendix A). Importantly, it is highly unlikely that families base their mobility decisions on expected sunshine hours in the destination district.

[3] We drop children with a height below 80cm and above 140cm and with a weight above 60kg and below 10kg.

After all, future sunshine hours in a specific district, conditional on district-by-year of birth and month of birth fixed effects—the key control variables in our regressions—are impossible to predict. We therefore may assign wrong sunshine hours in pregnancy and infancy for a small fraction of children, possibly leading to unsystematic measurement error in sunshine hours, biasing our estimates toward zero. Our estimates may therefore be best understood as a lower bound for the adiposity-reducing effects of additional sunshine hours in infancy.

The literature predominantly uses the Body Mass Index (BMI, weight in kilograms divided by height in meters squared) to calculate measures of childhood obesity. However, because they show fast gender-specific developmental changes, fixed cut-off rules for obesity for children similar to those for adults are not adequate. Therefore, childhood obesity is defined in gender- and age-specific growth curves in historic reference populations (e.g., Barlow, 2007). Usually, a BMI above the 85th percentile defines children as overweight, a BMI above 95th percentile as obese, and a BMI above 99th percentile as severely obese. Following the literature, we construct three main outcome variables: overweight, obesity, and severe obesity, defined, respectively, as > 85th, > 95th, and > 99th percentile in the gender- and age-specific (in months) BMI distributions in our data. The 85th percentile corresponds to a BMI cut-off of 17.07 for boys and 17.17 for girls, the 95th percentile to a BMI of 18.81 for boys and 18.90 for girls, and the 99th percentile to a BMI of 21.55 for boys and 21.70 for girls. These BMI cut-offs are in line with international samples that focus on children of similar ages (Centers for Disease Control and Prevention, 2000). We assess the robustness of our results by using internationally defined cut-off points for overweight and obesity, as suggested by Cole et al. (2000) based on data from more than 90,000 five to six year old children who were born in the 1980s and 1990s in Brazil, Great Britain, Hong Kong, the Netherlands, Singapore, or the

United States.[4] We use the metric BMI measure, as well as height and weight, as additional outcome variables to investigate whether sunshine hours affect the entire BMI distribution or only its upper tail, and to examine whether any effects on BMI are driven by reduced height or increased weight.

Table 1 provides a first descriptive overview of our sample. In our sample, boys are on average 120.5 cm tall and weigh 22.83 kg, compared to 119.6 cm and 22.45 kg for girls. The average BMI in our data is 15.65 for boys and 15.61 for girls. Based on the internationally defined cut-off points as in Cole at al. (2000), 11.70% of boys and 14.99% of girls in our sample are overweight, and 3.23% of boys and 4.00% of girls are obese. For comparison, in the US, the country with the highest adiposity levels in the sample of countries examined by Cole et al. (2000), 18.1% of boys and 16.5% of girls are overweight, and 3.3% of boys and 4.0% of girls are obese. The relatively high rates of adiposity in our sample are in line with studies showing that the prevalence of overweight and obesity for school children is relatively high in Germany in comparison to other countries and close to that in the US (e.g., Wang and Lobstein, 2006).

The findings in Panel A of Table 2 highlight that childhood obesity is associated with socio-economic background characteristics, in line with existing evidence (e.g., Wang and Zhang, 2006). Minority children (14.6% of our sample) are 2.7 percentage points or 19% more likely to be overweight, and 1.5 percentage points or 32% more likely to be obese than majority children.[5] Children of mothers with higher education (15.5% in our sample) are 22% less likely to be overweight and 34% less likely to be obese than children of mothers without higher

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[4] The BMI cut-off points for overweight at age 5.5, 6, and 6.5 are 17.45, 17.55, and 17.71 for boys and 17.20, 17.34, and 17.53 for girls. The respective BMI cut offs for obesity are 19.47, 19.78, and 20.23 for boys, and 19.34, 19.65, and 20.08 for girls. Cole et al. (2000) define no cut-off for severe obesity.

[5] Minority children are children whose parents migrated to Germany (for data from Weser-Ems) or children who do not have German citizenship (for data from Schleswig-Holstein). Information about migration background is not available in the state of Brandenburg.

education.[6] Children of fathers who are not employed (13.5% in our sample) are likewise more likely to be overweight (by 12%) or obese (by 28%).

The findings in Panel B of Table 2 further illustrate that childhood obesity correlates with district characteristics. The risk that a child is overweight or obese is 17 and 27 percent higher in districts with an unemployment rate above the mean. The associations between district GDP and measures of childhood obesity are slightly smaller.[7]

Table 3 and Figure 1 provide descriptive statistics of sunshine hours in our sample. On average, children in our sample experienced 1,223 hours of sunshine during pregnancy and 827 hours during their first six months of life. For comparison, average sunshine hours over one year are 2,771 in Athens, 2,524 in Barcelona, 1,625 in Berlin, 1,481 in London and 1,203 in Glasgow. The standard deviations of sunshine hours during pregnancy and the first six months of life are 231 and 285, respectively. Children born in November receive the most (1,481 hours) and children born in May the least (958 hours) hours of sunshine during pregnancy. In contrast, children born in April enjoy the most (1,186 hours) and children born in October the least (443 hours) sunshine hours during the first six months of life. In our sample, sunshine hours during pregnancy were on average highest for the 1990 birth cohort (1,349 hours) and lowest for the 1988 birth cohort (1,129 hours), while sunshine hours during the first six months of life were highest for the 1989 birth cohort (969 hours) and lowest for the 1998 birth cohort (691 hours). Children born in the districts of *Brandenburg a. d. Havel* and *Potsdam-Mittelmark* were on average exposed to the most sunshine hours, and children born in the district of *Leer* to the least sunshine hours during pregnancy and the first six months of life (1,326 versus 1,083 hours for pregnancy and 885 hours versus 735 hours for the first six months of life). These figures

[6] Mothers with higher education have either obtained a university degree (Brandenburg and Weser-Ems) or a school-leaving qualification that allows them to enter university (Schleswig-Holstein).
[7] Information on unemployment rate on district level is available since 1998. Information on GDP on district level is available since 2000.

illustrate that there is substantial variation in sunshine hours across districts, birth months and cohorts.

It should be noted that sunshine hours are generally higher in the federal state of Brandenburg (Panel C of Figure 1), a district in former East Germany, than in the two other West German states of Schleswig-Holstein and Lower Saxony. At the same time, the unemployment rate and GDP – both of which are, as shown in Panel C Table 1, associated with a higher obesity risk – are higher in Brandenburg than in the two other states. This correlation between sunshine hours and district characteristics underscores the need for a convincing identification strategy to isolate the causal effects of sunshine hours during pregnancy and in the first months of life on subsequent childhood obesity. We describe our identification strategy next.

4. Estimation Approach

Our baseline specification is a linear probability regression that links adiposity indicators of child *i* in district *r* born in year *y* and month *m* to the sum of hours of sunshine exposure in specific age intervals (indexed by the subscript *j*) from the onset of pregnancy until the child is 80 months old:

$$Adiposity_{i,r,y,m} = \sum_j \gamma^j \, Sunshine^j_{r,y,m} + \delta_{y,r} + \mu_m + \varepsilon_{i,r,y,m} \qquad (1)$$

Here, $Sunshine^j_{r,y,m}$ denotes total sunshine hours, divided by 100, during interval *j* for children residing in district *r* (there are 44 districts in our main sample), and born in year *y* (our sample includes 16 birth cohorts) and month *m*. In our baseline specification, we distinguish four age intervals: pregnancy; the first six months after birth; months six to eleven after birth; and months twelve to 80 after birth. In a more detailed specification, we distinguish eight age intervals: three 3-month intervals during pregnancy; four 3-month intervals during the child's first year of life; and one interval from the child's first birthday until she is 80 months old.

District-by-year of birth fixed effects are denoted by $\delta_{y,r}$, month of birth fixed effects by μ_m, and $\varepsilon_{i,r,y,m}$ is an error term. We cluster standard errors by "weather station districts"; that is, districts with unique weather station combinations. There are 44 districts, 21 weather stations and 28 "weather districts" in our main sample.[8]

The coefficients of interest γ^j measure how 100 additional sunshine hours in interval j affect adiposity at age six. By conditioning on district-birth-year fixed effects, $\delta_{y,r}$, we allow for the possibility that children and their parents in districts with more sunshine have a different upbringing, lifestyle and diet than children in less sunny districts (Sofi et al., 2014; Tucker and Gilliland, 2007). Children in districts with more sunshine may also generally differ from children in districts with less sunshine. District-by-year of birth fixed effects further account for the possibility that the state of the business cycle – which may be correlated with sunshine hours – affects child health (Dehejia and Lleras-Muney, 2004). Month of birth fixed effects μ_m address the concern that disadvantaged mothers (whose children tend to exhibit a larger risk of obesity) are more likely to give birth in seasons with less sunshine (Currie and Schwandt, 2013). This approach essentially exploits variation in sunshine hours that stems from some districts, but not others, receiving an unusual amount of sunshine (relative to the district average) in specific months of the year.

[8] The standard errors hardly change if we apply Conley standard errors (Conley, 1999) to account for spatially autocorrelated error structures.

5. Results

5.1 Baseline Results

We present our baseline findings based on regression equation (1) in Table 4. The estimates in column (1) show that increased sunshine hours during the first six months after birth reduce the adiposity risk at age six, regardless of which adiposity indicator is used. In contrast, the effects of sunshine during pregnancy, in months six to eleven after birth, or beyond the child's first year on childhood adiposity are considerably smaller in magnitude and not statistically significant from zero. To assess the magnitude of the impact of sunshine in the first six months of life, consider an increase of 100 sunshine hours – which is equivalent to the increased sun intensity from a two-and-a-half-week-long holiday in winter to a destination where sunshine is similar to that in summer. This reduces the probability of being overweight by 0.167 percentage points or, as 15% of children in our sample fall into this category, 1.1 percent (0.00167/0.15). Moreover, 100 additional sunshine hours reduce obesity and severe obesity by 0.129 and 0.062 percentage points, or 2.6 and 6.2 percent, respectively. In terms of absolute numbers of adipose children, these estimates imply 1,119 fewer overweight, 868 fewer obese, and 420 fewer severely obese children per birth cohort (677,947 children were born in 2010 in Germany) per 100 additional sunshine hours in the first six months after birth.

As mothers and infants do only spend part of the additional sunshine hours outside in the sun, our estimates should be interpreted as "intention-to-treat" estimates and should be considered as lower bounds for the impact of direct sunshine exposure on subsequent adiposity. Evenly spread over the first six months of life, 100 additional sunshine hours correspond to 33 minutes additional sunshine per day. To put this number into perspective, mothers would have to spend between 3 and 8 minutes in the sun (in Boston, MA, from April to October at 12 pm EST, Terushkin et al., 2010) to synthesize vitamin D levels equivalent to the recommended daily supplement for breastfeeding mothers (400 International Units).

To give an additional interpretation of the effect sizes, we compare them with the effect sizes of interventions targeted to reduce child obesity. One such intervention is the Head Start program. Two papers have found that participation in this program at ages 3 to 5 reduces the risk of overweight (by 26% among boys aged 12-13 according to Carneiro and Ginja, 2014) and obesity (by 2.3 percentage points (14%) independent of gender according to Frisvold and Lumeng, 2011). Although the effects of participation in Head Start in reducing childhood adiposity are considerably larger than the effects of 100 additional sunshine hours that we uncover (2.3 pp vs. 0.13 pp), such preschool programs are far more expensive than vitamin D supplementation.

In contrast, Prina and Royer (2014) do not find significant effects on children's obesity in an information intervention that aimed to increase parental knowledge and shift parental attitudes about children's weight in Mexico. In a similar vein, Bhattacharya et al. (2006) report that a school breakfast program in the US aimed to improve children's diets had no significant impact on children's risk of overweight or obesity. The latter two interventions clearly document the difficulties in implementing cost-effective strategies that reduce childhood obesity. The meta study by Brown et al. (2019) further illustrates this difficulty. This study includes 16 randomized control trials with the explicit goal of preventing obesity in children and focuses on children's BMI. The study finds that interventions that simultaneously target diet and physical activity reduced BMI by 0.07 kg/m^2. In contrast, interventions that target only diet or only physical activity did not significantly reduce BMI. In comparison, our estimates, discussed in Section 5 and presented in Figures 5 and 6, suggest that 100 additional hours sunshine during the first six months after birth decrease BMI at age 6 by 0.02 kg/m^2 for the whole population and by 0.11 kg/m^2 for those children in the highest BMI percentile.

Since the production costs of vitamin D supplements are low, our findings support the view that vitamin D supplementation in infancy are a cost-effective way to reduce childhood obesity.

5.2 Robustness Checks

Our findings are robust to adopting alternative estimation methods, the inclusion of additional control variables such as district-by-month of birth fixed effects, alternative measurements of sunshine hours, and the inclusion controls for weather.

Alternative specifications and control variables. We display estimates obtained from a probit model in column (2) of Table 4. Marginal effects from this specification are very similar in magnitude to those obtained from the linear probability model, presented in column (1). Flexibly controlling for age by including dummy variables for each age month group interacted with gender in equation (1) likewise hardly affects our estimates (column (3)). In column (4), we estimate an even tighter specification than our baseline specification and replace the month of birth fixed effects (μ_m in equation (1)) with district-by-month of birth and year of birth-by-month of birth fixed effects. Our results are largely unchanged. Column (5), adds dummy variables for each age month group interacted with gender (as in column (3)) to the specification estimated in column (5). Again, this has little impact on our estimates.

While the results so far refer to our baseline definitions of overweight, obesity, and severe obesity, we use internationally defined cut-off points to classify children as overweight and obese as in Cole et al. (2000) in column (6). The pattern remains the same: whereas sunshine hours in the first six months of life reduce the risk of childhood adiposity, sunshine hours during pregnancy and beyond the first six months of life have no significant impact on childhood adiposity. In terms of magnitude, estimates are similar to our baseline specification.

For example, 100 additional sunshine hours in the first six months after birth reduce the risk of overweight at age six by 0.22 percentage points or 1.7 percent, and the risk of obesity by 0.08 percentage points or 2.2 percent.[9]

Alternative measurements of sunshine hours. In columns (2) to (5) of Table 5, we explore the robustness of our results to alternative measurements of sunshine hours. For comparison, we report our baseline estimates as of column (1) of Table 4 in column (1). In column (2), we increase the distance rule to the next weather station and discard weather stations more than 50 miles (instead of 50 kilometers) away from the center of the district. In column (3), we only use information from the closest weather station, while in column (4) we uniformly weight across up to four weather stations in the district, to compute sunshine hours in each interval. Our estimates are very similar across alternative specifications.

Sunshine hours in winter months do not generate the same vitamin D levels in the body as sunshine hours in summer months as the sun is less intensive during this period. Moreover, infants' and mothers' skin may be largely covered due to low temperature. To account for this, we weight our baseline measure of sunshine hours with a sinus function, where the months June and July receive the highest weight of 1. Estimates, reported in column (5) of Table 5, are virtually identical to those in our baseline specification. This is not surprising as the specification controls for month of birth fixed effects and conditional on month of birth fixed effects, the baseline and weighted measures of sunshine hours are highly correlated.

Controlling for temperature and rainfall. Weather may have a direct impact on childhood obesity or early fetal development, conditional on sunshine (e.g., Barreca, Deschenes, and

[9] The overall rates for overweight and obesity following the international cut-off by Cole (2000) are 13.28 and 3.6.

Guldi, 2018). We probe the robustness of our estimates to the inclusion of weather controls in columns (6) and (7) of Table 5. Adding average daily temperature (column (6)) or cumulative rainfall (column (7)) in each of the four intervals as controls to our baseline specification barely changes our estimates. In Table B1 in Appendix B, we report results from a regression of children's adiposity risk on average daily temperature and cumulative rainfall, instead of sunshine hours, in each of the four intervals. Coefficients are consistently small in magnitude and not statistically significant from zero. Overall, these findings highlight that weather in pregnancy and infancy primarily affects childhood adiposity through sunshine hours rather than temperature or rainfall, as we would expect if vitamin D generation reduces the adiposity risk.

Placebo regressions. As a final specification check, we randomly assign "fake" sunshine hours to children in each of the four intervals from pregnancy to age 6 to check whether regressions of adiposity risk on "fake" sunshine hours produces equally large effects in the first six months of life as our baseline regression. To this end, we randomly draw a month of birth, a year of birth and a district for each child and assign sunshine hours in each interval accordingly. We then regress adiposity risk at age six on "fake" sunshine hours during pregnancy, months 0-5, months 6-12, and months 13-80, controlling for the same variables as in our baseline regression. We do this 300 times. In Figure 2, we plot the cumulative distribution of coefficients that we obtain from these "fake" or "placebo" regressions for the 0-5 months interval for which we find the largest effects. For all measures of adiposity, point estimates are closely centered around zero. For overweight, 13 out of the 300 point estimates are more negative than our baseline estimate of -0.165; for obesity and severe obesity, the number is even smaller (7 and 2, respectively). These findings cast some strong doubt that our estimates are simply spurious and driven by random variation in our data.

5.3 Additional Findings

Detailed Sunshine Intervals. In Figure 3, we distinguish eight (as opposed to four) sunshine intervals: seven 3-month intervals ranging from the beginning of pregnancy to the end of the child's first year and (as in Table 4) one interval from the child's first birthday until she is 80 months old. The figure once again visually illustrates that increased sunshine hours in the first six months of life (i.e., in intervals 0-2 and 3-5) reduce the risk of adiposity at age six. In contrast, increased sunshine hours in months six to eleven after birth or beyond the child's first year do not have a significant impact on childhood adiposity. In terms of magnitude, 100 additional sunshine hours in months three to six after birth reduce the risk of being overweight, obesity or severe obesity by 0.19, 0.18 and 0.09 percentage points or 1.3, 3.6 or 9 percent, respectively.

Non-linearity. So far, we have assumed that sunshine hours in three-month intervals from the start of pregnancy to the child's first year affect childhood adiposity in a linear way. We investigate the possibility of a non-linear relationship between sunshine hours in the first six months of life and subsequent childhood adiposity in Figure 4, by separating sunshine hours in the first six months of life into ten equally sized groups. In addition to these 10 dummy variables, we control for district-by-year of birth and month of birth fixed effects (as in equation (1)) as well as sunshine hours during pregnancy, months 6 to 11 and months 12 to 80 after birth (as in Table 4). The figure highlights that the relationship between sunshine hours in infancy and adiposity at age six is indeed roughly linear. For example, moving from the lowest to the highest decile – equivalent to an increase of 800 sunshine hours – reduces the risk of obesity by 1 percentage point, or 20 percent.

BMI, Weight and Height. Figure 5 shows the impact of sunshine exposure in eight detailed intervals on BMI, which is a combination of a child's weight and height. Panel A clearly shows that sunshine hours in the first six months of life significantly reduce BMI, but effects beyond six months after birth are close to zero and insignificant. Moreover, sun intensity in the last trimester of pregnancy also significantly lowers overall BMI.

In panels B and C of the Figure, we explore the impact of sunshine hours in pregnancy and infancy separately for height and weight. The graphs show that sunshine hours generally have little impact on children's height at age six, regardless of the sunshine interval. Even though the effect of increased sunshine hours on height is statistically significant for the interval three to five months after birth, the effect is very small in magnitude: 100 additional sunshine hours in that interval reduce height by 0.8 millimeters, implying an increase in BMI through the height channel of 0.013 percent if evaluated at mean weight and height for boys.

For weight, in contrast, a similar pattern as for our obesity measures emerges, and the negative impact of sunshine hours on weight at age six is concentrated in the first six months of life. The coefficient for the interval 3 to 5 months shows that 100 additional sunshine hours reduce weight at age 6 by 60 grams, implying a reduction in BMI through the weight channel of 0.26 percent if evaluated at mean weight and height for boys—an effect that is 20 times larger in magnitude than that through the height channel. The negative impact of sunshine hours in the first six months of life on average BMI at age six is therefore driven by a reduction in weight, and not an increase in height.

Effects along the BMI distribution. In a final step, we examine the effects of 100 additional sunshine hours in the first six months after birth along the BMI distribution at age six. To this end, we estimate unconditional quantile regressions based on equation (1) for each decile as well as the 95th and 99th percentile of the BMI distribution. The results, presented in Figure 6, show that while increased sunshine hours somewhat reduce BMI at all deciles, the effect becomes increasingly more negative at higher percentiles of the BMI distribution beyond the 80th percentile. This finding is important as higher BMI within the normal BMI range has no negative effects on health or medical costs; only children with an extreme BMI show worse health and generate high costs for the health system. The finding further suggests that increased sunshine exposure in the first six months of life prevents extreme cases of dysfunctional adipose tissue development and extreme forms of insufficient metabolism. More generally, the finding that the effects of increased sunshine hours are concentrated at the right tail of the BMI distribution mirrors those for bone density where additional vitamin D primarily benefits individuals with very low bone stability (Dawson-Hughes et al., 1997).

Heterogeneous Responses by Subgroups. Do the effects of sunshine hours in infancy on childhood obesity vary across children? We first distinguish between minority and majority children.[10] Minority children benefit more from additional sunshine exposure in infancy than majority children, for example because mothers of minority children are less likely to take vitamin D supplements (e.g., Moffat et al., 2015), or because of their darker skin color, which generally makes them more prone to vitamin D deficiency (e.g., Martin et al., 2016; Hintzpeter et al., 2008). Minority children are also more likely to be overweight or obese than majority children (see Table 2). The results in Appendix Table B2 tentatively suggest that sunshine hours in the first six months after birth reduce the risk of adiposity at age 6 more for minority than majority children. The difference in effects is, however, statistically significant only for the outcome of overweight.

[10] Information on minority status is available in only two federal states, Lower Saxony and Schleswig-Holstein, leading to a substantial reduction in sample size. See footnote 6 for a definition of minority status.

In a second step, we distinguish between who did and did not participate in all nine medical post-natal check-ups. The first three of these medical check-ups are conducted directly and in the days after birth. After that, check-ups take place 3, 6, 12, 24, 48, and 60 months after birth, conducted by pediatricians in hospitals or at their surgeries. Even though check-ups are compulsory, take-up is not complete and incomplete take-up is correlated with social disadvantage (Kamtsiuris et al., 2007). There is little evidence the effects of sunshine hours in infancy vary between children with complete and incomplete take-up (see Appendix Table B2).

6. Discussion and Conclusion

Based on administrative data from school entry examinations that cover all children in three large geographical areas in Germany and span 16 birth cohorts, combined with information on monthly sunshine hours obtained from 20 weather stations, our analysis shows that increased sun intensity in the first six months of life causally reduces the risk of overweight and obesity at age six, likely through higher vitamin D intake.

In terms of magnitude, 100 additional hours of sunshine in this time period, which is equivalent to the increased sun intensity from a two-and-a-half-week-long holiday in winter to a destination where sunshine is similar to that in summer, reduce the risk of being overweight at age six by 1.1 percent, the risk of obesity by 2.6 percent, and the risk of severe obesity by 6 percent. Sun intensity beyond the first six months of life, in contrast, has no discernible impact on subsequent adiposity. Sun intensity during the last trimester of pregnancy also reduces the risk of adiposity at age six, although this effect tends to be smaller in magnitude than during the first six months of life and is statistically significant in only some specifications.

We offer two main explanations for this pattern. First, the first six months of life (and possibly the third trimester of pregnancy) are a sensitive period for later obesity, as this is the period when infants rapidly gain weight and adipose tissue develops. Second, infants' vitamin

D levels are particularly sensitive to sunshine in the first six months of life, when lactation is highest.

Since we cannot observe the child's and mother's direct *exposure* to sunlight, our estimates should be interpreted as "intention-to-treat" estimates and should be considered as lower bounds for the impact of direct sunshine exposure on subsequent adiposity. Assuming that mothers of infants spend a third of their time in the sun during sunny days (which is likely to be an overestimate), our estimates imply that only 33 hours of additional direct sunshine exposure in the first six months of life—or 11 minutes per day—are required to induce a 1.1 percent reduction in the risk of overweight, and a 6 percent reduction in the risk of severe obesity at age six. Medical research suggests that spending 3 to 8 minutes in the sun in Boston, MA, from April to October at 12 pm EST synthesize 400 International Units (IU) of vitamin D (Terushkin et al., 2010), which is equivalent to the recommended daily supplement for breastfeeding mothers.[11] As the parts of Germany included in our study are located on a latitude more north than Boston and mothers unlikely receive additional sun mostly at 12pm when vitamin D generation is highest, our assumed 11 minutes additional sun per day will roughly lead to additional 400 IU of vitamin D. Therefore, our estimates may also give a hint to the effects of the daily intake of recommended vitamin D supplements.

Overall, a relatively small increase in direct sun exposure during the lactation period, or, alternatively, only the recommended amounts of vitamin D supplements for breastfeeding mothers, can reduce subsequent adiposity of their children. This finding is important for public health resource allocation. Since take-up of vitamin D supplements after birth is low, our results

[11] Terushkin et al. (2010) also present evidence that because of the well-known detrimental side effects of ultraviolet irradiation and the high effectivity of oral Vitamin D supplements, oral supplementation remains the safest way for increasing vitamin D levels. This result is supported by Wicherts et al. (2011) who, based on a randomized clinical trial, conclude that vitamin D supplementation is more effective than advised sunlight exposure in reducing vitamin D deficiency.

give further reasons, besides other proven effects of vitamin D, why governments should invest in campaigns to increase utilization of vitamin D supplements.

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Table 1: Descriptive Overview: Height, weight and BMI

		Girls	Boys
Height in cm			
	Mean	119.6	120.5
	standard deviation	5.37	5.39
Weight in kg			
	mean	22.45	22.83
	standard deviation	3.99	3.90
BMI			
	mean	15.61	15.65
	standard deviation	2.00	1.89
Adiposity risk based on internationally defined cut-offs			
Overweight			
	Share	0.15	0.12
	Mean BMI of overweight children	19.19	19.46
Obese			
	Share	0.04	0.03
	Mean BMI of obese children	21.53	21.82

Notes: The internationally defined BMI cut-offs are based on Cole et al. (2000). They define age and gender specific cut-offs for overweight and obesity.
Data source: School entry examinations, Schleswig-Holstein, Lower Saxony, Brandenburg.

Table 2: Obesity Risk by Socio-Economic Status and District Characteristics

	overweight (85th percentile)	obesity (95th percentile)	severe obesity (99th percentile)
Panel A: by Family Background Characteristics			
by minority status			
majority	0.143	0.046	0.008
minority	0.170	0.061	0.010
Number of observations		249,467	
by mother's education			
mother with higher education	0.127	0.038	0.008
mother without higher education	0.162	0.058	0.013
Number of observations		278,661	
by father's employment status			
father is employed	0.164	0.058	0.013
father is not employed	0.183	0.074	0.020
Number of observations		149,323	
Panel B: By District Characteristics			
by district unemployment rate			
district below mean	0.144	0.048	0.009
district above mean	0.168	0.061	0.014
Number of observations		464,003	
by district GDP			
district below mean	0.159	0.057	0.013
district above mean	0.149	0.051	0.011
Number of observations		365,389	

Notes: The table shows the share of overweight, obese and severely obese children at age six by parental background and district characteristics. Minority children are children whose parents migrated to Germany (for data from Weser-Ems) or children who do not have German citizenship (for data from Schleswig-Holstein). Information about migration background is not available in the state of Brandenburg. Mothers with higher education have either obtained a university degree (Brandenburg and Weser-Ems) or a school-leaving qualification that allows them to enter university (Schleswig-Holstein).

Data sources: School entry examinations, Schleswig-Holstein, Lower Saxony, Brandenburg and destatis (district characteristics).

Table 3: Sunshine During Pregnancy and First Months of Life: Descriptive Statistics

Panel A: Means and Standard Deviations

	sunshine hours during pregnancy	sunshine hours in first 6 months after birth
mean	1223.34	826.84
standard deviation	230.9	285.1
Number of observations	672,828	

Panel B: Variation in Sunshine Hours during Pregnancy in First Six Months of Life

	sunshine hours during pregnancy	Sunshine hours in first 6 months after birth
By Birth Month		
Birth Month with most sunshine hours	November	April
sunshine hours	1481	1186
Birth Month with lowest sunshine hours	May	October
sunshine hours	958	443.5
By Birth Cohort		
Birth Cohort with most sunshine hours	1990	1989
sunshine hours	1349	969
Birth Cohort with lowest sunshine hours	1988	1998
sunshine hours	1129	691
By District of Birth		
District with most sunshine hours	*Brandenburg a. d. Havel*	*Potsdam-Mittelmark*
sunshine hours	1326	885
District with lowest sunshine hours	*Leer*	*Leer*
sunshine hours	1083	735

Notes: Panel A displays the mean and standard deviation of sunshine hours in the first six months of life and during pregnancy. Panel B provides information on the variation in sunshine hours in the two intervals by birth month, birth cohort and district of birth.
Data sources: School entry examinations, Schleswig-Holstein, Lower Saxony, Brandenburg. Sunshine hours from 21 weather stations.

Table 4: Effects of Sunshine Hours During Pregnancy and First years of Life on Adiposity Risk at Age 6

	(1) Baseline	(2) Probit	(3) additional controls	(4) district-by-year and district-by-month of birth FE	(5) district-by-year and district-by-month of birth FE + additional controls	(6) inter-nationally defined cut-offs
Panel A: Overweight						
Sunshine hours in pregnancy	-0.062	-0.062	-0.055	-0.075	-0.070	-0.065
	(0.057)	(0.059)	(0.056)	(0.059)	(0.058)	(0.049)
Sunshine hours first 6 months of life	-0.167**	-0.161**	-0.154**	-0.115	-0.109	-0.217***
	(0.07)	(0.085)	(0.068)	(0.07)	(0.069)	(0.075)
Sunshine hours 6 to 11 months after birth	-0.032	-0.039	-0.022	-0.059	-0.050	-0.003
	(0.077)	(0.066)	(0.079)	(0.071)	(0.076)	(0.063)
Sunshine hours 12 to 80 months after birth	0.005	0.004	0.013	-0.002	0.008	-0.001
	(0.04)	(0.033)	(0.04)	(0.042)	(0.043)	(0.043)
Panel B: Obesity						
Sunshine hours in pregnancy	-0.035	-0.036	-0.031	-0.042	-0.039	-0.030
	(0.036)	(0.036)	(0.037)	(0.04)	(0.041)	(0.022)
Sunshine hours first 6 months of life	-0.129**	-0.125***	-0.122**	-0.097**	-0.094**	-0.079**
	(0.049)	(0.052)	(0.05)	(0.038)	(0.037)	(0.037)
Sunshine hours 6 to 11 months after birth	0.048	0.040	0.051	0.018	0.019	0.056
	(0.053)	(0.04)	(0.054)	(0.048)	(0.051)	(0.042)
Sunshine hours 12 to 80 months after birth	-0.008	0.010	-0.001	-0.029	-0.020	0.006
	(0.02)	(0.021)	(0.02)	(0.019)	(0.02)	(0.012)
Panel C: Severe Obesity						
Sunshine hours in pregnancy	-0.008	-0.008	-0.007	-0.018	-0.018	
	(0.014)	(0.016)	(0.013)	(0.014)	(0.013)	
Sunshine hours first 6 months of life	-0.062***	-0.057***	-0.062***	-0.063**	-0.066***	
	(0.021)	(0.023)	(0.021)	(0.023)	(0.023)	
Sunshine hours 6 to 11 months after birth	-0.002	-0.001	-0.003	-0.012	-0.013	
	(0.017)	(0.017)	(0.017)	(0.015)	(0.015)	
Sunshine hours 12 to 80 months after birth	0.002	0.003	0.001	-0.007	-0.008	
	(0.009)	(0.009)	(0.008)	(0.006)	(0.006)	
Number of Observations			666258			

Notes: The table shows the effects of 100 additional sunshine hours (in percentage points (pp.)) during pregnancy, in the first six months after birth, between months 6 to 12 after birth, and between months 12 and 80 after birth, on children's risk of overweight, obesity and severe obesity at age six. Overweight, obesity, and severe obesity are defined, respectively, as >=85th, >=95th, and >=99th percentile in the gender- and age (in months)-specific BMI distributions. In our baseline specification in column (1), we estimate linear probability models and control for, as in equation (1), district-by-year of birth and month of birth fixed effects. In column (2), we estimate probit models instead and report marginal effects. In column (3), we add detailed age-specific gender dummies as controls in the linear probability models. Results in column (4) expands our baseline specification in column (1) and includes district-by-year of birth, district-by-month of birth, and year of birth-by-month of birth fixed effects. In column (5) add to the specification in column (4) detailed age-specific gender dummies as controls (as in column (3). In column (6), we use internationally defined cut-off points to classify children as overweight and obese as in Cole et al. (2000). Cole et al. (2000) do not define a cut-off for severe obesity. Standard errors are clustered at the "weather station district" level (districts that are assigned different weather station combinations (28 clusters)). * p<0.1; ** p<0.05; *** p<0.01.

Data sources: School entry examinations, Schleswig-Holstein, Lower Saxony, Brandenburg. Sunshine hours from 21 weather stations.

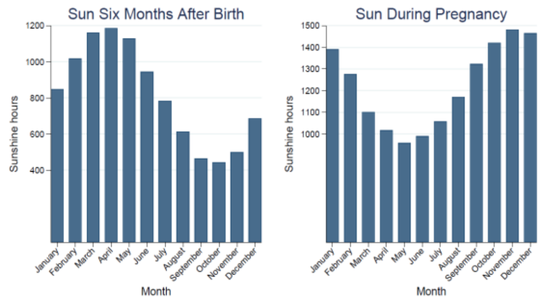
Table 5: Effects of Sunshine Hours During Pregnancy and First years of Life on Adiposity Risk at Age 6: Alternative Measurements of Sunshine Hours and Weather Controls

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
		alternative measures of sunshine hours				weather controls	
	Baseline	larger distance (50 miles)	uniform weighting	closest weather station	sinus function weighting of months	controls for average temperature	controls for cumulative rainfall
Panel A: Overweight							
Sunshine hours in pregnancy	-0.062	-0.038	-0.057	-0.066	-0.059	-0.113	-0.061
	(0.057)	(0.055)	(0.058)	(0.056)	(0.066)	(0.067)	(0.065)
Sunshine hours first 6 months of life	-0.167**	-0.187***	-0.161**	-0.175**	-0.142*	-0.215**	-0.180**
	(0.07)	(0.048)	(0.068)	(0.071)	(0.073)	(0.105)	(0.073)
Sunshine hours 6 to 11 months after birth	-0.032	-0.027	-0.034	-0.034	-0.022	-0.069	-0.096
	(0.077)	(0.064)	(0.076)	(0.07)	(0.086)	(0.066)	(0.085)
Sunshine hours 12 to 80 months after birth	0.005	0.016	0.000	-0.001	0.016	-0.042	0.008
	(0.04)	(0.037)	(0.04)	(0.026)	(0.046)	(0.045)	(0.043)
Panel B: Obesity							
Sunshine hours in pregnancy	-0.035	-0.030	-0.035	-0.033	-0.038	-0.070*	-0.051
	(0.036)	(0.028)	(0.037)	(0.035)	(0.041)	(0.038)	(0.04)
Sunshine hours first 6 months of life	-0.129**	-0.119***	-0.126**	-0.132***	-0.122**	-0.172***	-0.147***
	(0.049)	(0.039)	(0.049)	(0.048)	(0.05)	(0.06)	(0.047)
Sunshine hours 6 to 11 months after birth	0.048	0.043	0.043	0.049	0.054	0.026	0.026
	(0.053)	(0.034)	(0.053)	(0.049)	(0.059)	(0.048)	(0.051)
Sunshine hours 12 to 80 months after birth	-0.008	-0.004	-0.013	-0.006	-0.006	-0.023	-0.010
	(0.02)	(0.016)	(0.018)	(0.011)	(0.021)	(0.037)	(0.021)
Panel C: Severe Obesity							
Sunshine hours in pregnancy	-0.008	-0.007	-0.007	-0.008	-0.008	-0.013	-0.015
	(0.014)	(0.012)	(0.014)	(0.014)	(0.015)	(0.02)	(0.016)
Sunshine hours first 6 months of life	-0.062***	-0.038*	-0.060***	-0.066***	-0.061***	-0.077***	-0.065***
	(0.021)	(0.02)	(0.021)	(0.021)	(0.022)	(0.027)	(0.022)
Sunshine hours 6 to 11 months after birth	-0.002	0.002	-0.004	0.000	0.002	-0.024	0.004
	(0.017)	(0.017)	(0.017)	(0.016)	(0.019)	(0.02)	(0.019)
Sunshine hours 12 to 80 months after birth	0.002	0.006	0.001	-0.001	0.005	-0.016	0.002
	(0.009)	(0.009)	(0.009)	(0.005)	(0.01)	(0.016)	(0.01)
Number of Observations	666258	785686	666258	666258	666258	663898	665675

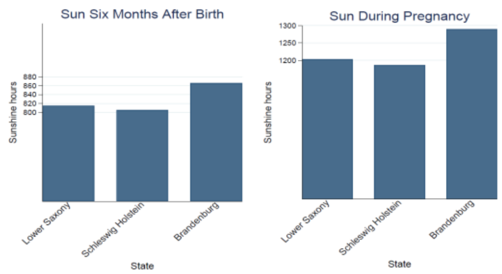
Notes: The table shows the effects of 100 additional sunshine hours (in percentage points (pp.)) during pregnancy, in the first six months after birth, between months 6 to 12 after birth, and between months 12 and 80 after birth, on children's risk of overweight, obesity and severe obesity at age six. Overweight, obesity, and severe obesity are defined, respectively, as >=85th, >=95th, and >=99th percentile in the gender- and age (in months)-specific BMI distributions. All columns estimate linear probability models and control for, as in equation (1), district-by-year of birth and month of birth fixed effects. Column (1) reports our baseline estimates based on up to four weather stations within 50 km radius. In column (2), we increase the radius to 50 miles (including all available 50 districts). In column (3), we apply a uniform weight to each weather station. In column (4), we only information on sunshine hours from the closest weather station. In column (5), we weight sunshine in each month by a sinus function by month where sunshine hours in June and July receive a weight of 1. In columns (6) and (7), we add average temperature and cumulative rainfall in the four intervals as additional controls to our baseline specification. Standard errors are clustered at the "weather station district" level, that is, districts with different weather station combinations (28 clusters). *Data sources*: School entry examinations, Schleswig-Holstein, Lower Saxony, Brandenburg. Sunshine hours from 21 weather stations. p<0.1; ** p<0.05; *** p<0.01.

Figure 1: Sunshine During Pregnancy and First Months of Life: Descriptive Statistics

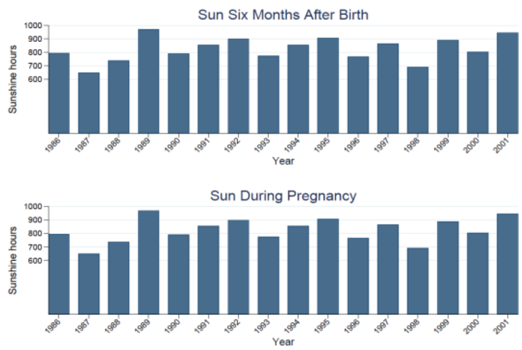
Panel A: by Birth Month



Panel C: By Federal State



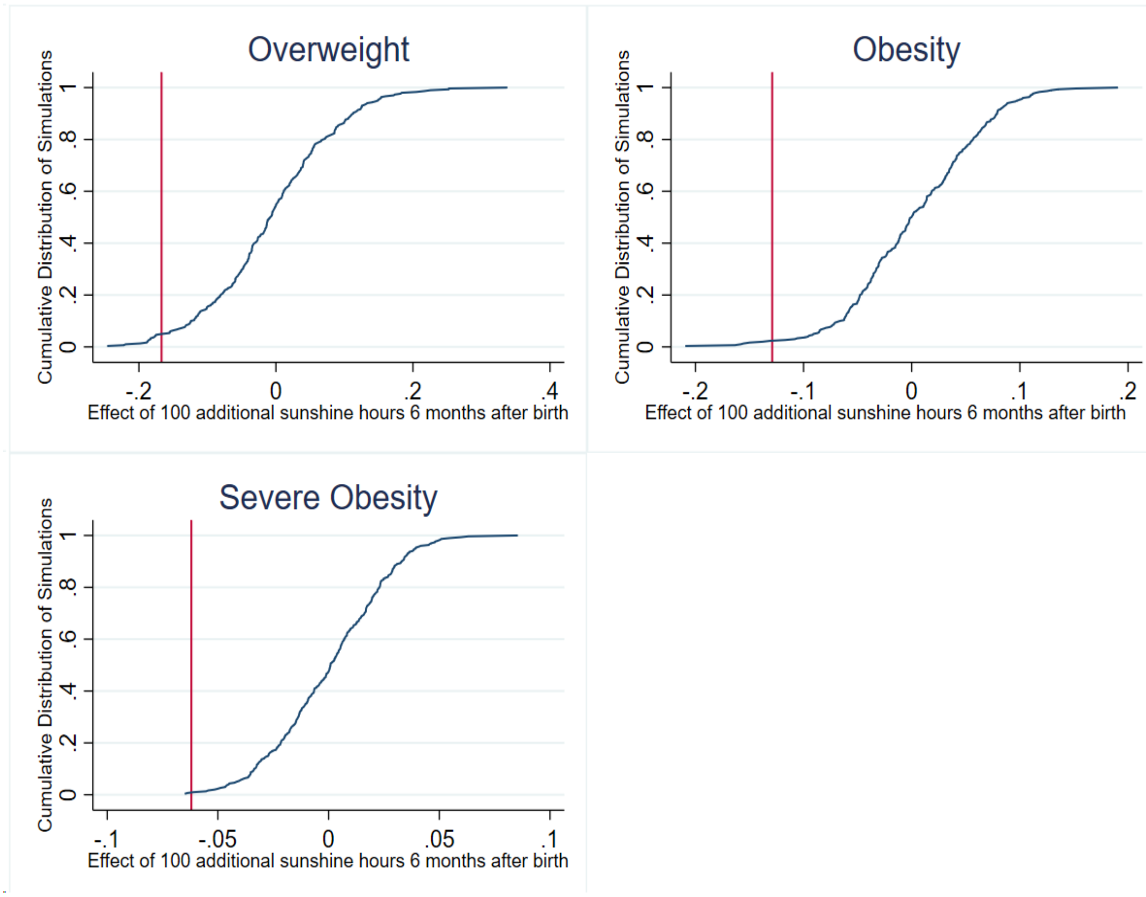
Panel B: By Birth Year



Notes: The figures display sunshine hours during the first six months after birth and during pregnancy by month of birth (Panel A), year of birth (Panel B), and district (Panel C) in our sample.

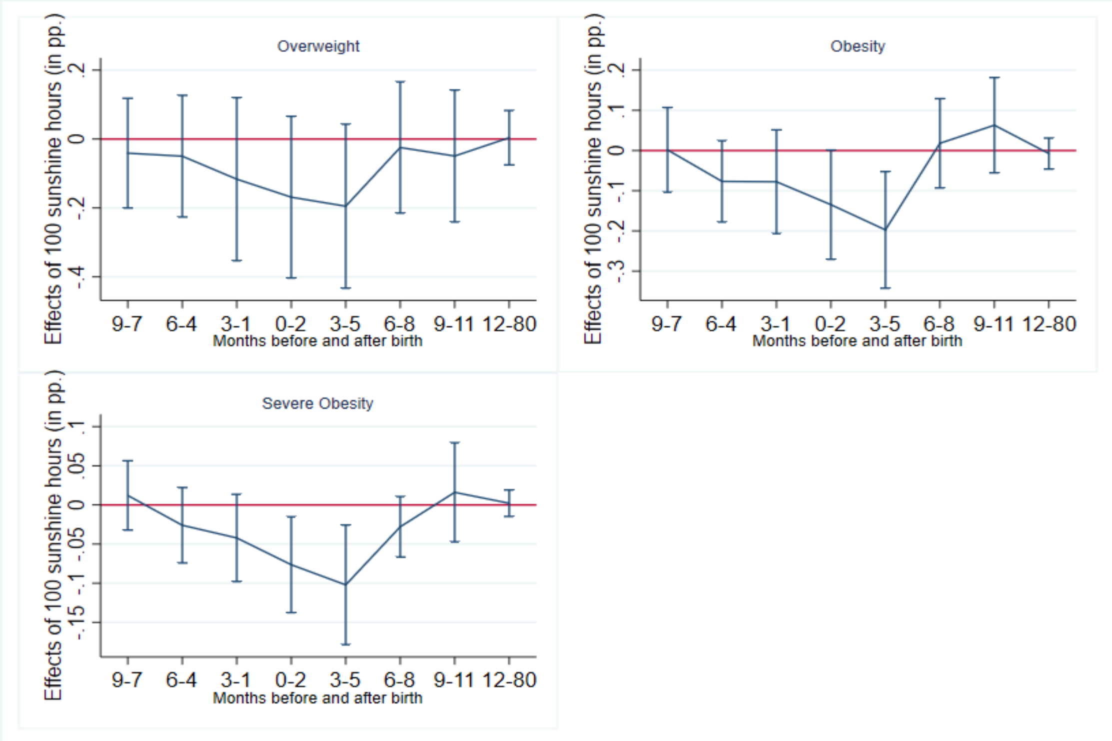
Data sources: School entry examinations, Schleswig-Holstein, Lower Saxony, Brandenburg. Sunshine hours from 21 weather stations.

Figure 2: "Placebo" Regressions of Adiposity Risk at Age 6 on "Fake" Sunshine Hours 0-6 Months After Birth



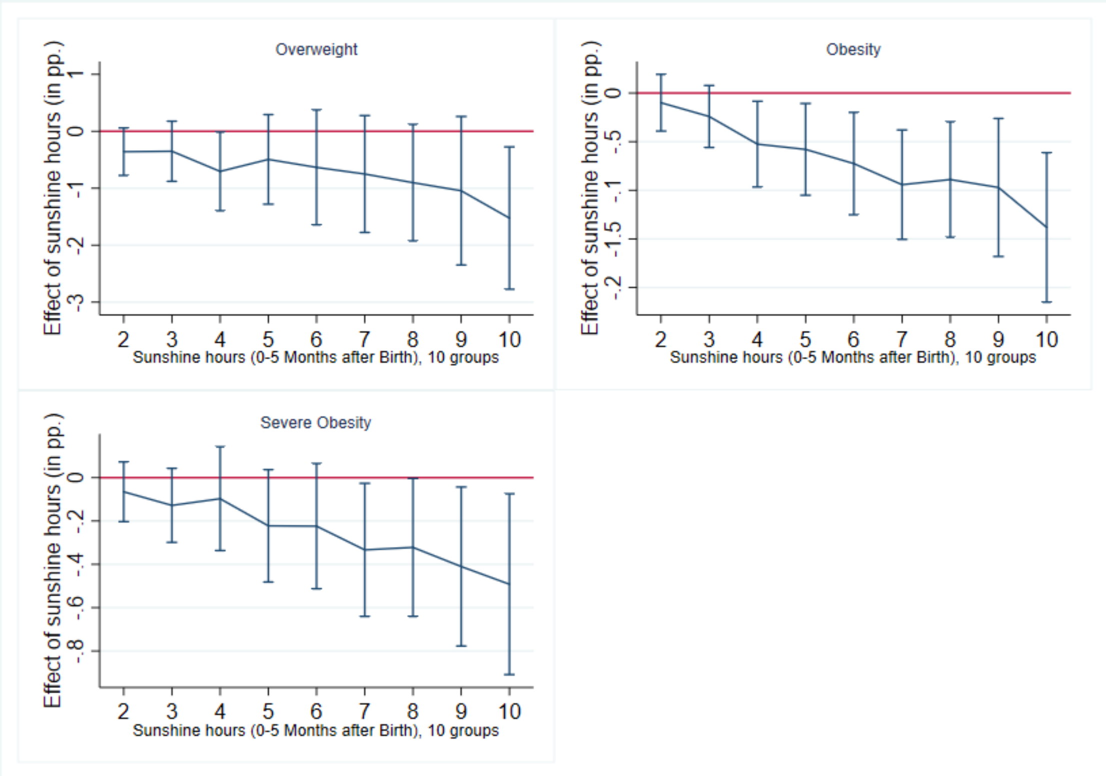
Notes: The figure displays the cumulative distribution of point estimates obtained from 300 regressions of adiposity risk at age 6 on "fake" sunshine hours for the interval 0-6 months after birth for which we find the largest effects. For each child in our sample, we randomly assign a month of birth, a year of birth and a district. We then compute "fake" sunshine hours during pregnancy, the first six months after birth, months 6-12 after birth, and months 13-80 after birth accordingly and regress our measures of adiposity risk at age 6 on "fake" sunshine hours in the four intervals, conditioning for the same set of control variables as in our baseline specification. We repeat this exercise 300 times. The red vertical line indicates our baseline point estimate. For overweight, 13 out of 300 "fake" point estimates are more negative than our baseline estimates; for obesity and severe obesity, the numbers are 7 and 2.
Data sources: School entry examinations, Schleswig-Holstein, Lower Saxony, Brandenburg. Sunshine hours from 21 weather stations.

Figure 3: Effects of Sunshine Hours During Pregnancy and First Years of Life on Adiposity Risk at Age 6



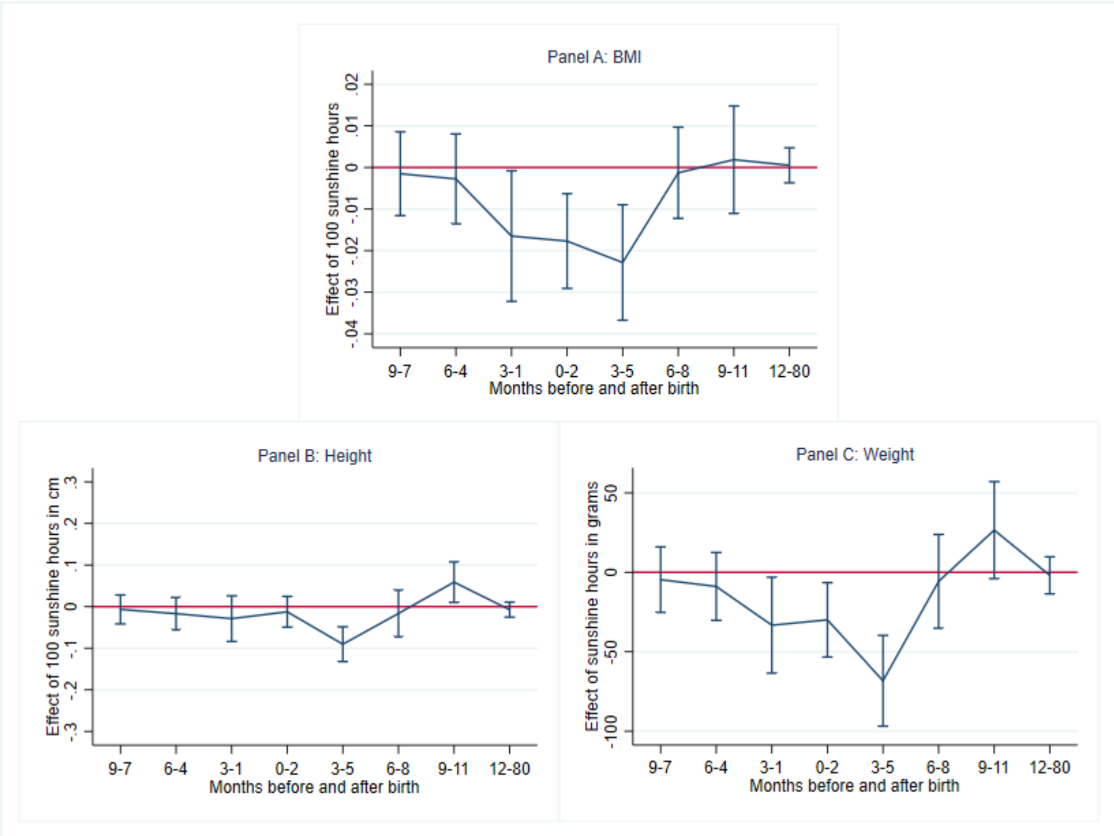
Notes: The figures show the effects of 100 additional sunshine hours (in percentage points (pp.)) in 3-month intervals from conception to 11 months after birth, and between 12 and 80 months after birth, on children's risk of overweight, obesity and severe obesity. Overweight, obesity, and severe obesity are defined, respectively, as >=85th, >=95th, and >=99th percentile in the gender- and age (in months)-specific BMI distributions. Effects are estimated by a linear probability model and regressions control for, as in equation (1), district-birth year and birth month fixed effects. The red horizontal line depicts a zero effect. The vertical lines show 95% confidence intervals calculated based on standard errors clustered at the "weather station district" level (districts that are assigned different weather station combinations (28 clusters)).
Data sources: School entry examinations, Schleswig-Holstein, Lower Saxony. Sunshine hours from 21 weather stations.

Figure 4: Non-Linear Effects of Sunshine Hours in First Six Months of Life on Adiposity Risk at Age 6



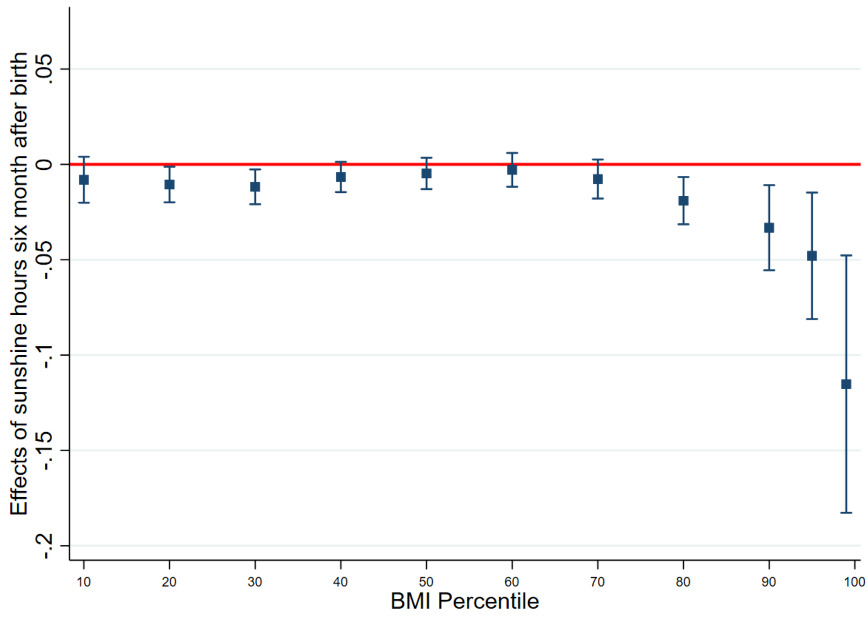
Notes: The figures plot the effects (in percentage points (pp.)) of sunshine hours in the first six months after birth, categorized in deciles, on children's overweight, obesity and severe obesity risk. Effects are estimated by a linear probability model and regressions control for, as in equation (1), district-birth year and birth month fixed effects. Overweight, obesity, and severe obesity are defined, respectively, as >=85th, >=95th, and >=99th percentile in the gender- and age (in months)-specific BMI distributions. Sun deciles are constructed by ranking districts by their sunshine hours in the first six months after birth and dividing them into 10 equally sized groups. For example, in the 2nd decile districts receive 491 sunshine hours on average, compared to 777 hours and 1,287 hours in the 5th and 10th decile. The red horizontal line depicts a zero effect. The vertical lines show 95% confidence intervals, based on standard errors clustered at the "weather station district" level (districts that are assigned different weather station combinations (28 clusters)).
Data sources: School entry examinations, Schleswig-Holstein, Lower Saxony, Brandenburg. Sunshine hours from 21 weather stations.

Figure 5: Effects of Sunshine Hours During Pregnancy and First Years of Life on BMI, Height and Weight at Age 6



Notes: Figure A shows the effects of 100 additional sunshine hours (in percentage points (pp.)) in 3-month intervals from conception to 11 months after birth, and between 12 and 80 months after birth, on children's BMI (Panel A), height (Panel B), and weight (Panel C). Effects are estimated by a linear probability model and regressions control for, as in equation (1), district-by-year of birth and month of birth fixed effects. The red horizontal line depicts a zero effect. The vertical lines show 95% confidence intervals, calculated based on standard errors clustered at the "weather station district" level (districts that are assigned different weather station combinations (28 clusters)).
Data sources: School entry examinations, Schleswig-Holstein, Lower Saxony, Brandenburg. Sunshine hours from 21 weather stations.

Figure 6: Effects of Sunshine Hours During the First Six Months of Life Along the BMI Distribution



Notes: The figure plots the effects of 100 additional sunshine hours on BMI in the first six months after birth along the BMI distribution. Each square shows the effect at a certain decile. Additionally, effects at the 95th and 99th percentile are shown. The vertical lines show 95% confidence intervals, based on standard errors clustered at the "weather station district" level (districts that are assigned different weather station combinations (28 clusters)).
Data sources: School entry examinations, Schleswig-Holstein, Lower Saxony, Brandenburg. Sunshine hours from 21 weather stations.