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Accessibility
Prenatal exposure to sand and dust storms and children’s cognitive function in China: a quasi-experimental study

Zhihui Li, Lincoln Chen, Mingqiang Li, Jessica Cohen

Summary
Background While there is evidence that sand and dust storms can have adverse health effects, the effects of such storms on children’s cognitive function has not been explored. We examined whether prenatal exposure to sand and dust storms affects children’s cognitive function and, if so, whether harmful effects of sand and dust storms vary by the trimester of exposure.

Methods This study used nationally representative data from the China Family Panel Studies between 2010 and 2014 and data on sand and dust storms from the national Sand and Dust Weather Almanac. We selected four indicators of children’s cognitive function: mathematics test scores, word-recognition test scores, the age the child began speaking in whole sentences, and the age the child began counting in whole sentences, and the age the child began counting from one to ten. Since the annual incidence of sand and dust storms is highly variable and is largely unpredictable, we used a region-and-year fixed-effect model to compare the cognitive function of children born in the same region and year but with varying amounts of prenatal exposure to sand and dust storms. We also investigated whether the effect of sand and dust storms varied by the specific month of prenatal exposure.

Findings We included 1236 observations for the analysis of mathematics and word-recognition test scores, 2693 observations in the analysis of the age the child began speaking in whole sentences, and 1951 observations for the analysis of the age the child began counting from one to ten. Every 10 additional days of prenatal exposure to sand and dust storms was associated with a 0·20 SD (95% CI 0·06 to 0·35, p=0·009) reduction in word test scores, 0·04 (–0·00 to 0·09, p=0·089) additional months to begin speaking in sentences, and 0·14 (0·03 to 0·25, p=0·021) additional months to begin counting, but was not significantly associated with mathematics test scores (reduction of 0·02 SD, –0·19 to 0·15). 10 additional days of prenatal exposure to sand and dust storms in the seventh gestational month was associated with a 0·18 SD (0·10 to 0·25) reduction in mathematics test scores, a 0·34 SD (0·18 to 0·50) reduction in word test scores, an additional 0·33 months (0·07 to 0·59) to begin speaking in sentences, and an additional 0·20 months (0·04 to 0·35) to begin counting.

Interpretation Our results suggest that protecting pregnant women from the effects of sand and dust storms in the critical periods of fetal brain development could generate benefits for the cognitive function of the next generation.

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Introduction Sand and dust storms occur worldwide and are particularly common in countries in the Middle East, central and south Asia, central and north Africa, and Australia, affecting roughly 2 billion people living in these regions.1 Sand and dust storms occur when a combination of strong winds and loose dry soil raise large quantities of dust into the air in arid and semi-arid areas.2 The storms are capable of transporting sediment over thousands of kilometers. For example, Saharan dust is transported to Amazonia, North America, Europe, the Middle East, and China.

Sand and dust storms in China are concentrated in the north of the country, with 14 and 65% of the total land area at risk. Sand and dust storms in China are highly seasonal, occurring mostly in the spring months.3 The incidence and intensity of the storms fluctuates greatly from year to year, depending on certain meteorological conditions and the dryness of the land.4 Sand and dust storms have complex compositions, with atmospheric mineral dust as the major component (85–94%), along with carbonates, spores, fungi, and bacteria.5 There is mounting evidence that sand and dust storms are associated with adverse effects on child health, including increases in mortality and the risk of respiratory, cardiovascular, and cardiopulmonary diseases.4–6 Several studies show evidence that prenatal exposure to dust events significantly lowers birthweight, reduces gestational time, and increases infant mortality.7,8 Although previous studies have shown short-term effects of sand and dust storm exposure on infants’ physical health, their longer-term effects on children’s cognitive function remained unexplored.

Results from animal studies have shown that inhaled air pollutants can be translocated from the respiratory system directly to the CNS, affecting cognitive processes.9–11 In studies in human beings, negative
Previous studies have shown that sand and dust storms are associated with adverse effects on child health through increased risk of respiratory diseases, cardiovascular diseases, and cardiopulmonary diseases. Yet there is very little evidence on the health effects of prenatal exposure to sand and dust storms. We searched PubMed, Web of Science, Google Scholar, and CNKI with the combination of terms “sand and dust storm”, “dust events”, “yellow storm”, “sand storm”, “dust storm” and “prenatal exposure”, “child development”, “child health”, “death”, “health effect”, “cognitive function”, and “cognitive development”, “test scores” in both English and Chinese on March 2, 2017. We identified only two studies, one in South Korea and one in west Africa, which investigated the short-term effects of prenatal exposure to sand and dust storms on children’s birth conditions and found significant negative associations. However, the longer-term effects of prenatal exposure to sand and dust storms on children’s cognitive function remain unexplored.

**Added value of this study**

To our knowledge, this is the first study to examine the long-term associations between prenatal exposure to sand and dust storms and children’s cognitive function. We obtained sand and dust storm data from the Sand and Dust Weather Almanac and nationally representative data on children’s cognitive function from China Family Panel Studies. With a quasi-experimental design, we examined the effects of prenatal exposure to sand and dust storms on children’s mathematics test scores, word-recognition test scores, the age at which the child began speaking in whole sentences, and the age at which the child began counting from one to ten. Prenatal exposure to sand and dust storms was associated with negative effects on cognitive function among children. The negative effects are most marked in the sixth and seventh gestational months.

**Implications of all the available evidence**

Our results suggest that countries experiencing sand and dust storms should have more policies in place to protect pregnant women from being exposed to them, particularly in the sixth and seventh gestational months. Further studies are needed to track the health effects of prenatal exposure to dust storms in the longer term, such as what happens when affected children enter adolescence, adulthood, and old age.

**Methods**

**Data sources**

Sand and dust storms are formally defined by the World Meteorological Organization (WMO) as the result of surface winds raising large quantities of dust into the air and reducing visibility at eye level (1·8 m) to less than 1 km. An annual Sand and Dust Weather Almanac (SDSWA) for China was published between 2000 and 2012. Following WMO guidance, the China Meteorological Administration defines sand and dust storms based on two conditions: visibility less than 1 km and observation of the storm at three or more neighbouring national ground meteorological stations (NGMSs). The observed unit of sand and dust storms used in this study is days of exposure in each month, so called dust days. These dust days are a measure of the intensity of sand and dust storms that has been widely used in previous research.11,19 Dust days reported by SDSWA are usually in the form of categories, such as 1–2 days or 3–4 days. We used the midpoints for each category—eg, if the category is 1–2 days, we code it as 1·5 dust days. To verify the accuracy of SDSWA categories and the appropriateness of using the category midpoints to measure the number of sand and dust days per month, we also simulated the incidence of sand and dust storms using the Integrated Wind Erosion Model System with data on wind field, soil variables, land use, and vegetation cover (see appendix).
Data on temperature, humidity, precipitation, and sunshine hours between 2000 and 2012 were obtained from the China Statistical Yearbook and regional Statistical Yearbooks for each city. Data are reported as monthly averages, calculated as the sum of daily average temperature, humidity, precipitation, or sunshine, divided by the number of days in that month. A full list of the datasets used for meteorological indicators is reported in the appendix.

Data on children’s cognitive function comes from the China Family Panel Studies (CFPS). CFPS is a nationally representative, longitudinal survey launched in 2010 and followed up in 2011, 2012, and 2014. The target sample of CFPS consists of 16,000 households in 25 provinces, municipalities, or autonomous regions in China, representing 95% of the Chinese population. The surveys include questions about the household overall and each household member. CFPS also collects information on the community in which the household is located. All eligible households and household members are included in the survey. An eligible household refers to an independent economic unit that lives in a residential community, with one or more family members of Chinese nationality. Family members are defined as financially dependent immediate relatives or non-immediate blood, marital, or adoptive relatives who have lived with the household for more than 3 consecutive months and are financially related to the sampled household. Within a sample household, all members older than 9 years are interviewed. More detail on the CFPS is available online.

As part of the CFPS, two sets of tests are administered to measure the cognitive function of all surveyed children aged 10 years and older: a mathematics test and a word-recognition test, with test items drawn from the standard curriculums in primary and secondary schools. The same cognitive tests were first conducted in 2010 and were followed up in 2011 and 2014. In every survey round, the respondent is also asked at what age their children began to speak in sentences and at what age their children began counting from one to ten.

**Study regions**

Sand and dust storms are heavily concentrated in the northern part of China and rarely occur in southern China. Thus we based our analysis on the regions located north of the Qinling Mountain-Huaihe River Line, which is typically used as a geographical dividing line between northern and southern China.

The CFPS does not publish information on county names. To go beyond the level of provinces, we used two types of geographical identifiers that are available in the CFPS data: the province in which the respondent lives and the dialect zones to which the respondent belongs. We combined the information on the boundaries of these two geographical identifiers and defined 40 province-dialect regions from the 16 provinces located north of the Qinling Mountain-Huaihe River Line. We included all 40 of these regions in our study. For each region, the number of dust days per month is calculated as the mean of the grid points (8 km x 8 km resolution) within the region. Since the meteorological data are provided at the city level, if multiple cities are included in one region, we calculated the meteorological values for that region using a weighted mean of each city. The weight is the actual area of that city included in the region.

**Outcomes**

The CFPS mathematics and word-recognition tests end when the individual incorrectly answers three questions in succession. The test scores are defined as the rank of the hardest question a respondent is able to answer correctly. Since the tests were applied to children of various ages, we standardised the test scores by age with the z-score method. Word and mathematics test scores have been widely used to measure children’s cognitive health in previous studies.

The cognitive tests only capture cognitive function for children older than 10 years, so, to further investigate the effect of sand and dust storms on the cognitive function of younger children, we adopted two self-reported indicators: first, the age (by month) that a child began speaking in whole sentence (eg, “I want to eat”), and second, the age (by month) that a child began counting from one to ten. Speaking capacities and counting skills are commonly used to analyse the cognitive performance of young children.

**Sample construction**

We had three exclusion criteria when constructing the sample for word-recognition and mathematics test scores (figure 1A). First, among all children aged 10–15 years old who were located in the study regions and had a gestational time between 2000–12 (when data on sand and dust storms were available), we only kept the records from the first survey if the children were tested in multiple surveys. Second, we excluded children who were located in a place other than their birth place when the surveys were conducted. We used this criterion because we could not identify their moving dates, which would be needed to control for the postnatal exposure to sand and dust storms. Moreover, since the children moved, a region fixed-effect model would be less effective for removing unobservable region-invariant confounders. Third, we followed previous practice and excluded children who were born preterm (less than 37 weeks or 8.5 months) or overdue (more than 42 weeks or 10 months).

Figure 1B shows how the samples for the ages at which children first spoke a whole sentence and counted from one to ten were constructed. First, we identified the records of all children who were located in the study regions and had gestational times between 2000–2012.
We included children aged 30–180 months old when the survey was conducted for speaking and 48–180 months for counting, which we based on the fact that 90% of the children in the sample had started speaking at 30 months and counting at 48 months. Second, if a child was surveyed multiple times but had inconsistent records, we used the report from the earliest survey because recall was most likely to be accurate for this timepoint. As with the test score samples, we excluded migrants and children who were born preterm or overdue.

**Statistical analysis**

We analysed the impact of prenatal exposure to sand and dust storms on cognitive outcomes with a region-and-year fixed-effect model. This model explored the association between fluctuations in sand and dust storms during the gestational period and outcomes for children born in the same region and year, controlling for various possible confounders.

The model is based on ordinary least square regression. We had four dependent variables: word test score, mathematics test score, age children began speaking in whole sentences, and age children began counting from one to ten. We did separate regressions for each of these four variables.

The independent variable was the total number of days that children were exposed to sand and dust storms during the gestational period. The CFPS provided caregiver-reported data on the date of birth for each child, as well as their gestational length. Using this information, we calculated the starting and ending dates of each child’s gestational period. Then, we generated the total number of days that the child was exposed to sand and dust storms during the gestational period. We divided the incidence of sand and dust storms by ten throughout this paper, so the coefficients of the independent variable represented the changes in outcomes that occurred with 10 more days of in-utero exposure to sand and dust storms.

We used a region-and-year fixed-effect model to eliminate the effects of unobservable region-invariant and year-invariant confounders. To manage regional- and year-fixed effects, we included a dummy for each region and a dummy for each gestational year. Since the gestational period might be spread over 2 years and because sand and dust storms are concentrated in the spring, we took the child’s gestational year to be the one that covers the spring. For example, if the gestational period for a child was from July, 2002, to April, 2003, we deemed 2003 to be the gestational year.

We controlled for all indicators listed in table 1, except for the days of exposure to sand and dust storms (the independent variable). Substantial evidence has shown that the child, parent, and household characteristics in table 1 are significantly associated with children’s cognitive development and are also potentially associated with prenatal exposure to harmful environmental pollutants, including sand and dust storms.

We controlled for postnatal exposure (within 1 year after birth) to sand and dust storms to eliminate the potential effects of postnatal exposure to sand and dust storms on children’s cognitive development. We also included dummies for the child’s calendar birth month as the

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**Figure 1: Sample selection**

Observations are those included in the analyses of (A) word recognition and mathematics test scores and (B) the age at which children began speaking in whole sentences and counting from one to ten.
covariates because birth month could be associated with both the child’s cognitive development, as well as the duration and timing of prenatal exposure to sand and dust storms. We included a monthly average of meteorological indicators (temperature, humidity, precipitation, and sunshine hours) during the entire prenatal period. We assumed that the error terms were normally distributed. The SEs were robust and clustered at the region level.

Since the ages at which the children began speaking in whole sentences and counting from one to ten were self-reported and therefore the data might be affected by recall bias, we did a sensitivity analysis by adding age-fixed effects into the regression. This model allowed us to investigate the association between sand and dust storms and cognitive outcomes in children who were the same age when the survey was conducted and who were born in the same region and year. Moreover, because of data limitations, we could not identify the amount of in-utero exposure to other pollutants in the analysis. The best data we can obtain regarding other pollutants are the annual average levels of SO₂ and NO₂ at the province level since we can obtain regarding other pollutants are the annual average levels of SO₂ and NO₂ at the province level since 2003, which are available from the China Statistical Yearbook. We included these two variables in the regression as a sensitivity test and the results are shown in the appendix.

To evaluate the fitness of our linear regression model, we followed established practice by plotting the residuals against the independent variable, detecting outliers, and checking the coefficient of determination R². The evaluation process is presented in the appendix.

Our second analysis investigated whether the effects of exposure to sand and dust storms varied by the gestational period in which the fetus was exposed. We again used a region-and-year fixed-effect model to remove the effects of omitted regional and year-invariant variables.

By comparison with our model on overall prenatal exposure to sand and dust storms, we replaced the aggregate days of prenatal exposure to sand and dust storms with the number of dust days that occurred during each gestational month, dummy variables for children’s gestational month, and the interaction terms of these two variables in the regression. For example, if a woman’s pregnancy period started from March 15, 2005, the first gestational month was March 15 to April 15, 2005. The number of sand and dust storm exposures in the first gestational month was the total number of dust days between March 15 to April 15 in that region in the year 2005. As mentioned previously, we divided the incidence of sand and dust storms by ten. The main parameter of interest was the interaction term, which showed the difference in the association between prenatal exposure to sand and dust storms and children’s cognitive function by gestational month. We plotted the coefficients of this interaction term to show how outcomes would change with 10 more days of prenatal exposure to sand and dust storms by gestational month. Besides the models adjusting for region-fixed and year-fixed effects and other covariates, we also did unadjusted regressions for overall prenatal exposure to sand and dust storms and exposure to sand and dust storms by gestational month. We used 0·1, 0·05, and 0·01 as the cutoff points for the significant levels. We followed established practice by plotting the coefficients of this interaction term to show how outcomes would change with 10 more days of prenatal exposure to sand and dust storms. BMI=body-mass index.

### Table 1: Sample characteristics by prenatal exposure to sand and dust storms

| Exposure to sand and dust storms, days | Exposure ≥6 days (n=1923) | Exposure ≤6 days (n=1143) | p value |
|---------------------------------------|---------------------------|---------------------------|---------|
| Children’s characteristics            |                           |                           |         |
| Age in 2014, years                    | 9·23 (0·15)               | 9·54 (0·21)               | 0·021   |
| Male sex                              | 1050 (54·6%)              | 601 (52·6%)               | 0·34    |
| Gestational age, months               | 9·36 (0·02)               | 9·39 (0·03)               | 0·20    |
| Height-for-age z score in 2014         | –0·11 (0·12)              | 0·21 (0·17)               | 0·55    |
| BMI-for-age z score in 2014            | 0·17 (0·11)               | 0·19 (0·13)               | 0·82    |
| Parents’ characteristics              |                           |                           |         |
| Mother’s education level in 2014       |                           |                           |         |
| Illiterate (not completed primary school) | 422 (21·9%)               | 284 (24·8%)               | 0·12    |
| Completed primary school               | 522 (27·1%)               | 304 (26·6%)               | 0·79    |
| Junior or senior high school           | 854 (44·4%)               | 491 (43·0%)               | 0·52    |
| College or higher                     | 125 (6·5%)                | 64 (5·6%)                 | 0·35    |
| Father’s education level in 2014       |                           |                           |         |
| Illiterate (not completed primary school) | 227 (11·8%)               | 172 (15·0%)               | 0·025   |
| Completed primary school               | 562 (29·2%)               | 310 (27·1%)               | 0·29    |
| Junior or senior high school           | 986 (51·3%)               | 563 (49·3%)               | 0·35    |
| College or higher                     | 148 (7·7%)                | 98 (8·6%)                 | 0·42    |
| Mother’s age in 2014, years            | 37·71 (0·33)              | 37·79 (0·39)              | 0·77    |
| Father’s age in 2014, years            | 39·43 (0·33)              | 39·58 (0·39)              | 0·57    |
| Living with mother in 2014             | 1642 (85·4%)              | 1022 (89·4%)              | 0·0068  |
| Living with father in 2014             | 1379 (71·7%)              | 879 (76·9%)               | 0·14    |
| Mother alive in 2014                   | 1913 (99·5%)              | 1137 (99·5%)              | 0·97    |
| Father alive in 2014                   | 1911 (99·4%)              | 1130 (98·9%)              | 0·23    |
| Maternal employment                   |                           |                           |         |
| Agricultural worker                    | 651 (33·9%)               | 472 (42·3%)               | <0·0001 |
| Non-agricultural worker                | 292 (15·2%)               | 183 (14·3%)               | 0·53    |
| Unemployed                            | 980 (51·0%)               | 508 (44·4%)               | <0·0001 |
| Household characteristics              |                           |                           |         |
| Urban place of residence               | 569 (29·6%)               | 271 (23·7%)               | 0·14    |
| Household income per capita, log scale | 8·66 (0·06)               | 8·63 (0·09)               | 0·61    |
| Family size in 2014                    | 5·34 (0·09)               | 4·83 (0·10)               | <0·0001 |
| Cooking fuel                           |                           |                           |         |
| Uncleaned cooking fuel, including wood, straw, and coal | 902 (46·9%)              | 590 (51·6%)               | 0·038   |
| Cleaned cooking fuel, including gas, solar energy, methane, electricity | 1021 (53·1%)              | 553 (48·4%)               | 0·0035  |

Data are n (%) or mean (SD) unless specified otherwise. 6 days was the median exposure to sand and dust storms during the entire prenatal period. Height-for-age z score and BMI-for-age z score were calculated in accordance with the WHO child growth standards. p values are for comparisons between children with below average and above average exposure to sand and dust storms. BMI=body-mass index.
Results

After exclusions, we kept 1236 observations for the analysis of word-recognition and mathematics test scores (figure 1A). 2693 children were included in the analysis of the age at which they spoke in sentences and 1951 children in the analysis of the age at which they counted from one to ten (figure 1B).

Figure 2 shows the distribution of days of sand and dust storms exposure by month between 2000–12, averaged across the studied regions. On average, sand and dust storms occurred for 3·0 days in each month during the spring (March, April, May) and 0·2 days in each month for the rest of the year. The distribution of children’s prenatal exposure to sand and dust storms is shown in the appendix. The median was 6·0 days (IQR 3·4–7·8) and the mean is 6·2 days (SD 4·14). The fifth quintile was at 8·4 days and the first quintile was at 3·1 days.

Table 1 shows summary statistics for key characteristics of the study sample. We divided the sample into children who had levels of prenatal exposure to sand and dust storms below the median (<6 days) and those who had exposure at or above the median (ie, ≥6 or more days) to explore whether these groups differed in any systematic way other than exposure to sand and dust storms. Most variables were similar for children with exposure above and below the median. On average, exposure to sand and dust storms was 3·36 days for the below-median group, which was significantly lower than the average of 9·87 days in the above-median group (p<0·0001). Compared with children in the below-median exposure group, children in the above-median exposure group seemed to be slightly older, more likely to live with their mothers, belong to families with fewer members, and have mothers who are agriculture workers, less likely to have an unemployed mother, and more likely to live in households using uncleaned fuel for cooking, and more likely to have an illiterate father. However, these differences were small in magnitude.

Table 2 shows the results from the fixed-effects model. Each 10 additional days of in-utero exposure to sand and dust storms was associated with a reduction of 0·20 SD (95% CI 0·06 to 0·35, p=0·009) in word-recognition test scores, but no significant change in mathematics test scores (–0·02 SD, –0·19 to 0·15, p=0·629). Additionally, each 10 additional days of exposure delayed the age at which children first spoke in whole sentences by 0·04 months (–0·00 to 0·09, p=0·089) and the age at which they first counted from one to ten by 0·14 months (0·03 to 0·25, p=0·021). The sensitivity analysis in the model with fixed effects for region, year, and age (appendix) showed consistent results. The sensitivity
analysis including SO\textsubscript{2} and NO\textsubscript{2} since 2003 also showed generally consistent results (appendix).

In the analysis of the interaction between gestational month and exposure to sand and dust storms, mathematics test scores, word-recognition test scores, and the age at which the child began speaking in whole sentences were negatively associated with exposure to sand and dust storms during the sixth, seventh, and eighth gestational months (figure 3). This finding suggests that the overall negative associations between prenatal exposure to sand and dust storms and cognitive health could have been driven by exposure during the sixth, seventh, and eighth months of gestation. The result was also similar in the age at which children began counting from one to ten, with negative associations during the sixth and seventh gestational months. No association was found for exposure to sand and dust storms in other gestational months.

The appendix shows the numerical values of the coefficients in figure 3, as well as the coefficients from our unadjusted models. The adjusted and unadjusted results were similar for all four outcomes. The unadjusted results seem to be similar in terms of both the coefficients and significance.

We conducted a series of sensitivity analysis, by including average levels of SO\textsubscript{2} and NO\textsubscript{2}, adding age-fixed effects, or involving the interaction term for cooking fuel and in-utero SDS exposure. The results of the sensitivity analysis were consistent with those of the main analysis.

**Discussion**

In our study, prenatal exposure to sand and dust storms was associated with poorer cognitive outcomes in children. The effect varied by the gestational month in which exposure occurred. We found that exposure to sand and dust storms during the sixth and seventh months of gestation was significantly associated with poorer future cognitive function, with consistent results across statistical models. The magnitude of these effects seems to be large—eg, as exposure to sand and dust storms increased from the first quintile (0·5 days) to the fifth quintile (4·0 days) during the seventh gestational month, children’s test scores were reduced by 0·06 SD for mathematics and 0·12 SD for word-recognition.
(appendix). The ages at which children started speaking in sentences and counting to ten were also delayed by an average of 0.11 months and 0.07 months, respectively (appendix). These findings are reminiscent of the general fetal origins hypothesis, which proposes that prevailing conditions during the crucial periods of prenatal growth have long-term effects on developmental health.

Our results align well with the previous evidence from animal studies showing that fetal brains are easily affected by environmental pollutants because the development of the blood-brain barrier in the fetus is incomplete and fetal brains are sensitive to any pollutant-triggered changes in bloodborne substances.\textsuperscript{9–11} Recent studies in human beings have also provided evidence that ambient and indoor pollutants could cross the placenta and damage the fetal brain, probably by inducing inflammation, oxidative stress, and vascular injury.\textsuperscript{12–14} A few studies have also investigated the effects of pollutants by trimesters of exposure, but the results were inconclusive and potentially biased by confounders.\textsuperscript{9,15}

Compared with previous studies in human beings, one key strength of this study is that we were able to identify an association between exposure to prenatal sand and dust storms and children’s cognitive function with strong causal inference. Because the incidence and intensity of sand and dust storms varies greatly by year and season and is hard to predict beforehand, people cannot choose which years to be pregnant in to avoid them. On the basis of this feature, we adopted a region- and-year fixed-effect model to compare children who were in the prenatal period in the same region and year, but with varying incidence of prenatal exposure to sand and dust storms. In this way, we could effectively remove the effect of unobservable region-specific and year-specific variables that do not vary over time. The records on each child’s gestational time and birth date further allowed us to identify the amount of exposure to sand and dust storms in each gestational month and look into the effects of this exposure by gestational month. Moreover, our study design also makes use of formalised tests on cognitive assessment and detailed monitoring of various potential confounding factors.

This study has several limitations. First, we cannot fully exclude the effects of other pollutants, such as NO\textsubscript{2}, SO\textsubscript{2}, and O\textsubscript{3}, because we did not have sufficient data. Although we did a sensitivity analysis by including annual average levels of SO\textsubscript{2} and NO\textsubscript{2} since 2003 in the regression, we acknowledge that the annual data do not capture seasonal variations in SO\textsubscript{2} and NO\textsubscript{2}. However, many studies have reported that levels of these pollutants are highest in winter months and have only minor annual fluctuations, which supports our assumption that the occurrence of sand and dust storms is not correlated with levels of other pollutants.\textsuperscript{30} Moreover, by controlling for the child’s birth month, we are comparing the effects of prenatal exposure to sand and dust storms among children born in the same month with similar exposure to other pollutants.

Second, the data on the age at which children began speaking in sentences and counting from one to ten might be affected by recall bias. To address this issue, when the children were surveyed repeatedly with these questions in different survey rounds, we used the answers from the first survey. We also conducted a sensitivity analysis that included age-fixed effects to study the association between sand and dust storms and cognitive outcomes among children who were the same age when the survey was administered and born in the same region and year. Results were similar to those in the main model.

Third, we cannot fully exclude the effects of indoor pollutants, nor can we control for the pregnant women’s behavioural patterns during sand and dust storms. For example, if women were more likely to stay indoors during sand and dust storms, they might be less exposed to sand and dust storms but more exposed to indoor pollutants, causing the estimations to change in an unknown direction. To control for the potential effects of indoor pollutants, we included the types of cooking fuels in the analysis. We compared the results from regressions with and without the variable for cooking fuel (appendix) and found that the coefficient on sand and dust storm exposure was essentially unchanged across the two specifications and the coefficients for cooking fuel were not significant. We also included a sensitivity analysis with the interaction term for cooking fuel and in-utero sand and dust storm exposure (appendix). The coefficients for the interaction terms were not significant, suggesting that the associations between in-utero exposure to sand and dust storms and children’s cognitive function did not differ significantly with the types of cooking fuel used in the household. However, this method suffered from the fact that CPFS only reported the types of cooking fuel used at the time the surveys were administered, which could differ from the type of cooking fuel used during the woman’s pregnancy, and the types of cooking fuels cannot fully represent the effects of all indoor pollutants.

Fourth, we cannot account for stillbirths or infant or child deaths in our study. The less healthy babies might have died prenatally or during infancy before being able to appear in the survey. This could lead to underestimation of the association between exposure to sand and dust storms and cognitive function. Fifth, we cannot fully exclude migrants from the analysis. Pregnant mothers might choose to temporarily move out from their usual home to avoid exposure to sand and dust storms and move back in after it was over. This migration might not be random and could systematically affect our results in an unknown direction. Sixth, we cannot tell whether the effects of sand and dust storms are generalisable to children outside of our sample (i.e., those not meeting the exclusion criteria). Seventh, we cannot test the mechanisms by which pollutants might affect children’s cognitive function.
Although previous studies in animals or human beings have provided some evidence that the inhalation of air pollutants during pregnancy affects the development of the fetal CNS, none of the studies focused specifically on sand and dust storms. Finally, the strong winds and the dry soil surfaces, the two necessary conditions for the occurrence of sand and dust storms, might affect maternal and child health through other channels, such as reducing food productivity, triggering infectious diseases, or affecting electricity and water supply.

Despite these limitations, our study is, to our knowledge, the first to investigate the effects of prenatal exposure to sand and dust storms on children’s cognitive function. Our results suggest that in-utero exposure to sand and dust storms could have long-lasting adverse effects on children’s cognitive development, particularly when exposure occurred during the sixth and seventh gestational months. Although this study could provide strong causal inference, more research is needed to replicate these results and identify the short-term and long-term effects of in-utero exposure to sand and dust storms on children’s health. It will also be important to generate more clinical evidence on the mechanisms behind these findings.

Contributors
ZL, ML, and JC designed the study. ZL and ML collected and cleaned up the data. ZL did the literature review, conducted the quasi-experimental analysis, interpreted the results, and wrote the draft paper, with contributions from ML, LC, and JC. All authors commented on the draft and revised version of the paper and approved the submission texts.

Declaration of interests
We declare no competing interests.

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