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RESEARCH ARTICLE

# Maternal exposure to cooking oil fumes during pregnancy and autistic-like behaviors in Chinese preschoolers

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## Abstract

There is growing evidence that cooking oil fumes (COFs) are harmful indoor air pollutants. However, there is a dearth of research investigating whether maternal COFs exposure during pregnancy may affect children's autistic-like behaviors in China. This study aimed to explore this association, and examine the effects of different cooking fuels and ventilation methods used by mothers on the presence of autistic-like behaviors. This study analyzed the survey data of the Longhua Child Cohort Study in 2017 with a total of 62,372 mothers enrolled in this study. A self-administrative questionnaire was used to collect information on socio-demographic characteristics, cooking habits during pregnancy, and autistic-like behaviors (measured using the Autism Behavior Checklist). After adjusting for potential confounders, the results showed that compared with children whose mothers never cooked during pregnancy, children whose mothers cooked sometimes, often, always during pregnancy had the higher risk of autistic-like behaviors. As the amounts of COFs exposed to and the frequency of cooking during pregnancy increased, the risk of a child's autistic-like behaviors also increased. Mothers using natural gas as cooking fuels had a lower risk of their child having autistic-like behaviors, compared with mothers using coal or other cooking fuels. Furthermore, pregnant women using ventilation measures during cooking significantly decreased likelihood of the presence of autistic-like behaviors in their children. These results suggest that maternal exposure to COFs during pregnancy may increase the likelihood of the presence of autistic-like behaviors in offspring. These findings support a recommendation that pregnant women should avoid exposure to COFs and use clean fuels and ventilation equipment in kitchens to reduce the risk of autistic-like behaviors in children.

**Keywords** Cooking oil fumes · Cooking habits · Preschooler · Autistic-like behaviors · Pregnancy · Neurodevelopment

## Introduction

Autism spectrum disorder (ASD) includes a range of neurodevelopmental conditions characterized by varying degrees of difficulty in social interaction, difficulties in verbal and nonverbal communication, and repetitive behaviors (American Psychiatric Association 2013; Lai et al. 2014). The World Health Organization (WHO) estimated the global prevalence of ASD as being approximately 1% in 2012 (Elsabbagh et al. 2012). The prevalence rates in the Western countries, such as America, Canada, and British are 1.85%, 1.52%, and 1.47%, respectively (Maenner et al. 2020; Ofner et al. 2018). However, in Asian countries, the prevalence of ASD appears to be relatively lower than the Western countries and has been estimated as being 0.29% for China and 0.23% for India (Rudra et al. 2017; Zhou et al. 2020), respectively.

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The etiology of ASD remains unclear. Previous studies demonstrated that ASD and autistic-like behaviors have similar genetic and environmental risk factors (Bolte et al. 2019; Robinson et al. 2011), such as a lack of nutrition, vitamins, and folic acid during pregnancy and prenatal exposure to heavy metals and air pollution (Kalkbrenner et al. 2014; Lyall et al. 2014). Despite extensive research focused on assessing the association between outdoor air pollution exposure and autistic traits in children, there are limited studies exploring the relationship of indoor air pollution with autistic-like behaviors in children (Kalkbrenner et al. 2014; Lyall et al. 2014). Furthermore, the limited evidence that there is an association between air pollution exposure and autistic traits in children have been mostly drawn from developed countries (Gong et al. 2017; Raz et al. 2018; Roberts et al. 2013). In China, with culturally specific cooking habits that are the main source of indoor air pollution (S. Y. Cheng et al. 2016a, b; Yu et al. 2015), the contributions of COFs exposure on preschoolers' neurodevelopment outcomes may be greater than that found in Western countries.

Cooking oil fumes (COFs) have been recognized as a main source of indoor air pollution (Liu et al. 2020; Wang et al. 2017; Yu et al. 2015). COFs are composed of the toxic compounds, such as particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), nitrogen oxides ($NO_x$), and volatile organic compounds (VOCs) (S. Y. Cheng et al. 2016a, b; Ke et al. 2016; Lu et al. 2019; Peng et al. 2017). In China, due to its traditional food culture, people are used to cooking foods in the home using a variety of cooking styles (such as deep-frying, grilling, frying, and quick-frying), which tend to emit high levels of COFs (Wang et al. 2017). Indoor air pollution results in significant detrimental health effects with more than 4 million people dying each year due to indoor air pollution exposure (WHO 2014). There is an abundance of evidence to support a link between COFs exposure and the development of chronic diseases such as lung cancer (Lee & Gany 2013), chronic bronchitis (H. C. Chen et al. 2018a, b), fatty liver (Lin et al. 2020), and a series of respiratory symptoms (Juntarawijit & Juntarawijit 2017). Moreover, it has been well documented that maternal prenatal COFs exposure can increase the risk of adverse birth outcomes including low birth weight (LBW) (Hu et al. 2018; Jiang et al. 2015), large for gestational age (LGA), and preterm birth (Wang et al. 2018). Furthermore, two studies in Spain indicated that pregnant women's exposure to gas cooking was linked to the presence of preschooler's neurodevelopmental delay (Morales et al. 2009; Vrijheid et al. 2012), and our recent study found that maternal exposure to COFs during pregnancy might increase the risk of children's hyperactive behaviors (Fang et al. 2020).

To the best of our knowledge, no study has focused on the association between prenatal cooking exposure and offspring's autistic-like behaviors. Thus, in the present study, we assess the association between maternal exposure to COFs in pregnancy and the risk of autistic-like behaviors in Chinese children. In addition, we also examined if taking some mitigation measures, such as the use of different cooking fuels and the utilization of ventilation equipment in cooking, are protective against the risk of autistic-like traits in young children.

## Subjects and methods

### Study population

The Longhua Child Cohort Study (the LCCS) was designed to examine the impact of family and school environment on children's early life psycho-behavioral development in Longhua district, Shenzhen, Guangdong (Ruan et al. 2017). Preschoolers were enrolled in the LCCS at their entrance to kindergarten, and their mothers were contacted to complete a self-administered questionnaire. The inclusion criteria of the LCCS included all children and their mothers who (1) registered in the kindergarten system in Longhua District, Shenzhen, (2) lived with their children and took care of their children for more than 1 year, and (3) understood the purpose and significance of this study and signed an informed consent form. The exclusion criteria were children with severe physical illness or mental disorders, including birth defects (Harris et al. 2017) such as cardiovascular/heart defects; musculoskeletal defects and so on; and mothers with serious mental illnesses like schizophrenia spectrum disorders, bipolar disorder and paranoid disorder (McClellan 2018), or who did not sign an informed consent form. This paper used the data from the LCCS survey administered in 2017. After excluding 5,489 (5,489/6,7861 = 8.1%) participants due to mothers not providing complete information, a total of 62,372 (62,372/67,861 = 91.9%) child-mother pairs were included in the final data analysis. The demographic characteristics for those included and excluded from this paper were compared in Supplementary Table A.

The study was approved by the Ethic Committee of School of Public Health of Sun Yat-sen University in Guangzhou, China (No. 2015–016). Written informed consent was acquired from all primary caregivers who participated in the study. The study was conducted in accordance with the Declaration of Helsinki.2.2 Data collection.

### Data collection

The mothers of enrolled preschoolers were asked to fulfill a self-administered questionnaire enquiring the socio-demographic characteristics of children and parents (such as age, gender, marital status, education level, family income,

occupation), maternal cooking habits during pregnancy, and parental ratings of autistic-like behaviors of their children.

### Measurement of maternal exposure to COFs

Maternal cooking habits during pregnancy were measured with the following five questions. (1) When you were pregnant with your child, who is now attending preschool, did you ever cook? Response options were 0 for "no," and 1 for "yes." (2) If yes, what was the frequency of cooking? Response options were 1 for "sometimes," 2 for "often," and 3 for "always." (3) If yes, what amounts of COFs did you experience when you cooked? Response options were 1 for "little," 2 for "medium," and 3 for "a lot of." (4) If yes, what type of cooking fuels was used? Response options were 1 for "coal gas," 2 for "natural gas," 3 for "electricity," and 4 for "coal and other." (5) If yes, what methods did you use to ventilate when you cooked? Answer options were 1 for "none," 2 for "exhaust hood used," 3 for "extractor fan used," and 4 for "window opened." For the frequency of cooking, we defined those who cooked at least one time every 2 to 4 weeks during pregnancy as "sometimes cooking," those who cooked at least once per week during pregnancy as "often cooking," and those who cooked at least once every day during pregnancy as "always cooking."

### Measurement of autistic-like behaviors

The Autism Behavior Checklist (ABC) was used to measure the children's autistic-like behaviors in this study. The tool has been widely used around the world since its development in 1980 and used in individuals aged from 18 months to 35 years for screening ASD (Krug et al. 1980). The ABC contains 57 items (scored 1 to 4) according to its relevance to autism: sensory behaviors, relating behaviors, body and object using behaviors, language behaviors, and social and self-help behaviors (Goldstein & Naglieri 2011). The total ABC score was calculated by adding the scores of all items and ranged from 0 to 158, where a higher score indicated a higher level of autistic-like behaviors. ABC was introduced into China by Yang et al. and recommended the cut-offs of score $\geq 31$ for screening of ASD in Chinese children, which showed good reliability and validity (Yang et al. 1993). Thus, in this study, we used a score of 31 as the cut-off point for screening autistic-like behaviors in the Chinese people.

### Covariates

Based upon previous published literature (Gardener et al. 2009; Kim et al. 2011; Yousefian et al. 2018; X. Zhang et al. 2010a, b), we first selected a child's gender and age, parental education level, family monthly income, parental age at the time of the child's birth, marital status, passive smoking during pregnancy, preterm birth, and birth weight as potential confounders in this study. Then, a directed acyclic graph (DAG, Figure A in Supplementary) was constructed based on the existing literature to select a minimally sufficient set of covariates (DAGitty v3.0 software, http://www.dagitty.net). Based on the DAG, the following variables were used as covariates in our analysis: paternal and maternal age at childbirth, paternal and maternal education level, family monthly income, marital status, and maternal passive smoking during pregnancy (Figure B in Supplementary).

### Statistical analyses

For the descriptive analysis, means and standard deviations (SD) were used to describe continuous variables, while frequencies and percentages were used to describe categorical variables. Differences in socio-demographic characteristics between participants with and without ASD traits were examined using independent sample Student's *t*-tests for continuous variables and chi-squared tests for categorical variables.

A series of binary logistic regression analysis were performed to investigate the strength of association, as well as the dose–response relationship, between maternal exposure to COFs during pregnancy and the presence of autistic-like behaviors in their child, after adjusting for the aforementioned covariates. To explore the effects of ventilation methods on the likelihood of the presence of the children's autistic-like behaviors, all mothers (47,750) who cooked during pregnancy were divided into twelve groups depended on the combinations of exposure to COFs and methods of ventilation. A cross-over analysis was performed via the logistic regression model with adjustment for the potential confounders.

Statistical significance was defined as $p < 0.05$. All statistical analyses were performed in R versions 4.0.2 (R Foundation for Statistical Computing, Vienna, Austria).

## Results

### Socio-demographic characteristics among participants

Three percent (1,871/62,372) of preschoolers had autistic-like behaviors. The comparison of socio-demographic characteristics between preschoolers without and with autistics-like behaviors is presented in Table 1. The frequency of boys was significantly higher in those with autistic-like behaviors compared with those without autistic-like behaviors. The mean age (4.62 years) of children with autistic-like behaviors was younger than those without autistic-like behaviors. In addition, the children with autistic-like behaviors, compared with those

**Table 1** Comparison of socio-demographic and obstetric characteristics among children with and without autistic-like behaviors

| Characteristics | Total ($N=62,372$) | Autistic-like behaviors | | | $\chi^2$/t | $P$ |
|---|---|---|---|---|---|---|
| | | No ($N=60,501$) | Yes ($N=1871$) | % | | |
| *Child sex (%)* | | | | | 59.615 | < 0.001 |
| Boy | 33,773 | 32,596 (53.9) | 1177 (62.9) | 3.61 | | |
| Girl | 28,599 | 27,905 (46.1) | 694 (37.1) | 2.43 | | |
| *Child age (mean (SD))* | 62,372 | 4.62 (0.88) | 4.34 (0.90) | | 12.732 | < 0.001 |
| *Maternal education level (%)* | | | | | 200.430 | < 0.001 |
| Junior high school or lower | 15,659 | 14,950 (24.7) | 709 (37.9) | 4.74 | | |
| High school | 33,755 | 32,821 (54.2) | 934 (49.9) | 2.85 | | |
| College or higher | 12,958 | 12,730 (21.0) | 228 (12.2) | 1.79 | | |
| *Maternal occupation (%)* | | | | | 30.028 | < 0.001 |
| Employed | 52,957 | 51,452 (85.0) | 1505 (80.4) | 2.93 | | |
| Housewife | 9415 | 9049 (15.0) | 366 (19.6) | 4.04 | | |
| *Paternal education level (%)* | | | | | 202.922 | < 0.001 |
| Junior high school or lower | 12,717 | 12,111 (20.0) | 606 (32.4) | 5.00 | | |
| High school diploma | 31,594 | 30,686 (50.7) | 908 (48.5) | 2.96 | | |
| College or higher | 18,061 | 17,704 (29.3) | 357 (19.1) | 2.02 | | |
| *Family income, RMB/month (%)* | | | | | 173.059 | < 0.001 |
| < 5000 | 9188 | 8788 (14.5) | 400 (21.4) | 4.55 | | |
| 5001–10,000 | 16,874 | 16,231 (26.8) | 643 (34.4) | 3.96 | | |
| 10,001–20,000 | 20,884 | 20,351 (33.6) | 533 (28.5) | 2.62 | | |
| > 20,000 | 15,426 | 15,131 (25.0) | 295 (15.8) | 1.95 | | |
| *Marital status (%)* | | | | | 2.274 | 0.131 |
| Single | 1535 | 1479 (2.4) | 56 (3.0) | 3.79 | | |
| Married | 60,837 | 59,022 (97.6) | 1815 (97.0) | 3.08 | | |
| *Single child or not (%)* | | | | | 0.010 | 0.921 |
| No | 33,773 | 32,762 (54.2) | 1011 (54.0) | 3.09 | | |
| Yes | 28,599 | 27,739 (45.8) | 860 (46.0) | 3.10 | | |
| *Maternal age at child birth* | 62,372 | 27.04 (4.15) | 25.91 (4.36) | | 11.048 | < 0.001 |
| *Paternal age at child birth* | 62,372 | 29.60 (4.73) | 28.59 (5.00) | | 8.613 | < 0.001 |
| *Maternal BMI before pregnancy* | 62,372 | 20.36 (4.76) | 20.31 (2.77) | | 0.6781 | 0.498 |
| *Passive smoking during pregnancy (%)* | | | | | 113.879 | < 0.001 |
| No | 44,729 | 43,592 (72.1) | 1137 (60.8) | 2.61 | | |
| Yes | 17,643 | 16,909 (27.9) | 734 (39.2) | 4.34 | | |
| *Preterm birth (%)* | | | | | 14.543 | < 0.001 |
| No | 57,639 | 55,953 (92.5) | 1686 (90.1) | 3.01 | | |
| Yes | 4733 | 4548 (7.5) | 185 (9.9) | 4.07 | | |
| *LBW (%)* | | | | | 25.335 | < 0.001 |
| No | 58,854 | 57,138 (94.4) | 1716 (91.7) | 3.00 | | |
| Yes | 3518 | 3363 (5.6) | 155 (8.3) | 4.61 | | |

without autistic-like behaviors, were significantly more likely to have mothers or fathers with junior high school rather than college education, have mothers who were housewives rather than being employed, have a lower family income, have lower maternal and paternal ages, were more likely to have mothers who engaged in passive smoking during pregnancy, were more likely to have been born preterm, and were more likely to have been born with low birth weight. There was no significant difference between the children with and without autistic-like behaviors on mother's marital status, being a single child or not, and maternal body mass index (BMI) before pregnancy in children.

## Associations between prenatal exposure to COFs and children's autistic-like behaviors

As shown in Table 2, compared to those who never cooked during pregnancy, pregnant women who cooked during

pregnancy had a significantly greater likelihood of having a child with autistic-like behaviors (*AOR* = 1.54, 95% CI = 1.35–1.76). Furthermore, we also analyzed associations of mothers COFs exposure during pregnancy with the total ABC scores and the subscale scores in preschoolers. We found that compared with those mothers who did not expose to COFs, those who exposed to COFs during pregnancy had a significantly higher level of autistic-like behaviors and five subscales at preschoolers (Please see Table B in Supplementary).

Table 3 presents the results of the associations between maternal prenatal COFs exposure and the presence of children's autistic-like behaviors after adjusting for potential confounders. Compared to those who never cooked during pregnancy, pregnant women exposed to "a little," "medium," or "a lot of" COFs had a significantly increased risk of autistic-like behaviors in their child, with their adjusted *AOR*s being 1.49 (95% CI = 1.30–1.71), 1.57 (95% CI = 1.36–1.81), and 2.10 (95% CI = 1.59–2.74) respectively. Furthermore, the risk of autistic-like behaviors increased with the increase of cooking frequency with the adjusted ORs of 1.19 (95% CI = 1.04–1.38) for "sometimes," 1.66 (95% CI = 1.42–1.95) for "often," and 2.29 (95% CI = 1.96–2.67) for "always."

As illustrated in Table 4, among subgroups with the same amounts of COFs (i.e. no, little, medium, or a lot of), the risk of autistic-like behaviors was greater with the increase of frequency of cooking. Furthermore, compared with the reference group of those whose mother did not cook during pregnancy, the likelihood of the offspring exhibiting autistic-like behaviors was significantly higher in (1) pregnant mothers reporting little exposure to COFs and cooking sometimes (*AOR* = 1.20, 95% CI = 1.03–1.40), often (*AOR* = 1.73, 95% CI = 1.40–2.13), or always (*AOR* = 2.42, 95% CI = 2.01–2.90); (2) in pregnant mothers reporting medium exposure to COFs and cooking often (*AOR* = 1.63, 95% CI = 1.37–1.95) or always (*AOR* = 2.14, 95% CI = 1.78–2.56); and (3) in pregnant mothers reporting a lot of exposure to COFs and cooking always (*AOR* = 2.51, 95% CI = 1.80–3.41).

## Associations between using preventive measures during cooking and children's autistic-like behaviors

After controlling for the potential confounders, pregnant women who cooked using natural gas (*AOR* = 0.66, 95% CI = 0.51–0.87) had a lower risk of autistic-like behaviors in their child, compared to mothers who cooked using coal or others fuels during

**Table 2** Associations between maternal cooking exposure during pregnancy and children's autistic-like behaviors

| *Cooking* | Total (*N* = 62,372) | Case (*N* = 1871, %) | COR (95%) | *AOR* (95% CI)[a] |
|---|---|---|---|---|
| No | 14,622 | 280 (1.90) | 1.00 | 1.00 |
| Yes | 47,750 | 1591 (3.30) | 1.77 (1.56, 2.01)*** | 1.54 (1.35, 1.76)*** |

[a]Adjusting for maternal and paternal age at childbirth, maternal and paternal education level, family monthly income, marital status, and maternal passive smoking during pregnancy

***$p < 0.001$

**Table 3** Associations of maternal COFs exposure during pregnancy with autistic-like behaviors

| Variables | Total (*N* = 62,372) | Case (*N* = 1871, %) | *COR* (95%) | *AOR* (95% CI)[a] |
|---|---|---|---|---|
| *Amounts of COFs* | | | | |
| None | 14,622 | 280 (1.9) | | 1.000 |
| A little | 26,284 | 843 (3.2) | 1.70 (1.48, 1.95) | 1.49 (1.30, 1.71)*** |
| Medium | 20,025 | 680 (3.4) | 1.80 (1.57, 2.08) | 1.57 (1.36, 1.81)*** |
| A lot of | 1441 | 68 (4.7) | 2.54 (1.92, 3.30) | 2.10 (1.59, 2.74)*** |
| *P* for trend | | | | < 0.001 |
| *Frequency of cooking* | | | | |
| Never | 14,622 | 280 (1.9) | | 1.000 |
| Sometimes | 24,599 | 674 (2.7) | 1.44 (1.25, 1.66) | 1.19 (1.04, 1.38)* |
| Often | 11,031 | 390 (3.5) | 1.88 (1.61, 2.19) | 1.66 (1.42, 1.95)*** |
| Always | 12,120 | 527 (4.3) | 2.33 (2.01, 2.70) | 2.29 (1.96, 2.67)*** |
| *P* for trend | | | | < 0.001 |

*COFs*, cooking oil fumes

[a]Adjusting for maternal and paternal age at childbirth, maternal and paternal education level, family monthly income, marital status, and maternal passive smoking during pregnancy

*$p < 0.05$; ***$p < 0.001$

**Table 4** Associations of autistic-like behaviors with combinations of amounts of COFs and frequency of cooking exposure

| COFs exposure | | Total ($N=62,372$) | Case ($N=1871$, %) | *COR* (95% CI) [a] | *AOR* (95% CI) [a] |
|---|---|---|---|---|---|
| *Amounts of COFs* | *Frequency of cooking* | | | | |
| None | Never | 14,622 | 280 (1.9) | | 1.00 |
| Little | Sometimes | 16,875 | 464 (2.7) | 1.45 (1.25, 1.68)*** | 1.20 (1.03, 1.40)* |
| | Often | 3901 | 135 (3.5) | 1.84 (1.49, 2.26)*** | 1.73 (1.40, 2.13)*** |
| | Always | 5508 | 244 (4.4) | 2.37 (1.99, 2.83)*** | 2.42 (2.01, 2.90)*** |
| | *P* for trend | | | | < 0.001 |
| Medium | Sometimes | 7554 | 204 (2.7) | 1.42 (1.18, 1.71)*** | 1.17 (0.97, 1.41) |
| | Often | 6766 | 241 (3.6) | 1.89 (1.59, 2.25)*** | 1.63 (1.37, 1.95)*** |
| | Always | 5705 | 235 (4.1) | 2.20 (1.84, 2.62)*** | 2.14 (1.78, 2.56)*** |
| | *P* for trend | | | | < 0.001 |
| A lot of | Sometimes | 170 | 6 (3.5) | 1.87 (0.73, 3.91) | 1.53 (0.60, 3.21) |
| | Often | 364 | 14 (3.8) | 2.05 (1.13, 3.41)* | 1.63 (0.90, 2.72) |
| | Always | 907 | 48 (5.3) | 2.86 (2.07, 3.88)*** | 2.51 (1.80, 3.41)*** |
| | *P* for trend | | | | < 0.001 |

*COFs*, cooking oil fumes

[a]Adjusting for maternal and paternal age at childbirth, maternal and paternal education level, family monthly income, marital status, and maternal passive smoking during pregnancy

*$p<0.05$; ***$p<0.001$

pregnancy. Moreover, a lower likelihood of a child exhibiting autistic-like behaviors was found when the mother cooked using a kitchen ventilator (*AOR* = 0.53, 95% CI = 0.44–0.64), extractor fan (*AOR* = 0.64, 95% CI = 0.52–0.78) or with an open window (*AOR* = 0.76, CI = 0.63–0.93), compared to those who cooked without using any ventilation measure (Table 5).

## Discussion

In this study, we found that maternal COFs exposure during pregnancy was positively associated with the presence of autistic-like behaviors in preschool children, with a dose–response relationship between both the frequency of cooking and amounts COFs exposure, and the likelihood of offspring's autistic-like behaviors. Moreover, we observed that pregnant women who cooked using natural gas or exhaust hood as a ventilation measure could significantly decrease the subsequent likelihood of autistic-like behaviors in preschool children.

Our findings are consistent with the emerging research on the relationship between maternal COFs exposure during pregnancy and children's poor neurodevelopment. For example, two studies from Spain both found that pregnant women's exposure to gas cooking might increase the presence of neurodevelopmental disorders

**Table 5** Associations between preventive measures for cooking and autistic-like behaviors

| Variables | Total ($N=47,750$) | Case ($N=1591$, %) | *COR* (95% CI) | *AOR* (95% CI) [a] |
|---|---|---|---|---|
| *Type fuels of cooker used* | | | | |
| Coal or others | 2220 | 90 (4.1) | | 1.00 |
| Coal gas | 33,035 | 1137 (3.4) | 0.84 (0.68, 1.06) | 0.86 (0.69, 1.08) |
| Natural gas | 7108 | 154 (2.2) | 0.52 (0.40, 0.69)** | 0.66 (0.51, 0.87)** |
| Electricity | 5387 | 210 (3.9) | 0.96 (0.75, 1.24) | 0.98 (0.77, 1.27) |
| *Methods of ventilation* | | | | |
| No | 2463 | 133 (5.4) | | 1.00 |
| Kitchen ventilator | 25,880 | 706 (2.7) | 0.49 (0.41, 0.60)*** | 0.53 (0.44, 0.64)*** |
| Extractor fan use | 9345 | 325 (3.5) | 0.63 (0.51, 0.78)*** | 0.64 (0.52, 0.78)*** |
| Window opening | 10,062 | 427 (4.2) | 0.78 (0.64, 0.95)* | 0.76 (0.63, 0.93)** |

[a]Adjusting for maternal and paternal age at childbirth, maternal and paternal education level, family monthly income, marital status, and maternal passive smoking during pregnancy

**$p<0.01$; ***$p<0.001$

in their offspring (Morales et al. 2009; Vrijheid et al. 2012). Similarly, our previous study revealed that maternal cooking during pregnancy increased the risk of children's hyperactivity, and a similar relationship was also identified between the cooking frequency and the risk of hyperactive behaviors (Fang et al. 2020). Taken together, all these studies support the conclusion that maternal exposure to cooking fumes during pregnancy can exert an adverse impact upon children's neurobehavioral development. Furthermore, we found a significant dose–response relationship between the amounts of COFs during pregnancy or the frequency of cooking and the likelihood of autistic-like behaviors in preschoolers. However, in our study, we did not utilize objective equipment to exactly measure or assess mothers who exposed to the amounts of COFs. Thus, future research should use objective methods to measure the amounts of COFs exposed to during cooking.

With the development of a social economy and the improvement of health awareness, people are gradually switching from polluting (e.g. wood, coal) to clean (e.g. gas, electricity) cooking fuels which will reduce air pollutants from cooking (Shupler et al. 2019). This is important given that our previous research showed that using clean fuels during pregnancy could reduce the presence of hyperactivity in subsequent children, comparted to using coal fuels (Fang et al. 2020). Two studies in Spain found that maternal exposure to gas fuels during pregnancy was a risk factor for poor mental development in offspring, compared with those who cooked using electricity during pregnancy (Morales et al. 2009; Vrijheid et al. 2012). Similarly, our present study found a significantly negative relationship between the frequency of women cooking using natural gas during pregnancy and the likelihood of autistic-like behaviors in their offspring, compared with those who cooked using coal or other fuels during pregnancy. However, we did not observe a significant negative association between pregnant women cooking using electricity and the likelihood of their off-springs' autistic-like behaviors compared with pregnant women cooking with coal or other fuels. This might be due to the high proportion of mothers using a kitchen ventilator (84.1%) which may remarkably decrease COFs in kitchens (C. Chen et al. 2018a, b), in the natural gas subgroup compared with the other three subgroups (Table C in Supplementary). Furthermore, mothers who used electricity to cook were more likely to cook by means of deep-frying, pan-frying, and stir-frying and cook for longer, all of which generate more hazardous pollutants when compared with the single way of cooking in Western culture (Wang et al. 2017), as well as the different cooking ingredients, food, and oil used between Chinese and the Western (Cheng et al. 2016a, b; Lee et al. 2001; Peng et al. 2017), which might contribute to this results in our study. Further research is needed to explore and understand these associations.

In the past few decades, ventilation measures such exhaust hoods and ventilation fans have been commonly used to exhaust cooking pollutants to improve air quality in kitchens. For example, Chen and colleagues found that the removal efficiency of the exhaust hood was more than 55% for fine particles ($PM_{2.5}$), nearly 49% for ultrafine particles (UFPs), and $68 \pm 8\%$ for formaldehyde during Chinese-style cooking (C. Chen et al. 2018a, b), which significantly decreased the effect of COFs on human health. A study in Spain showed that extractor hoods, which reduced nitrogen dioxide concentrations ($NO_2$) during cooking, were a protective factor for poor neuropsychological development furthermore; this study found that children whose mothers used their extractor hoods less during pregnancy were more likely to have children with poor mental development (Vrijheid et al. 2012). Consistent with these previous findings, our study also found a protective effect of pregnant women using ventilation measures, such as exhaust hoods and extractor fans, during cooking on the presence of autistic-like behaviors in their off-springs.

The potential mechanisms by which COFs may impair neurodevelopment in children have not been established yet. However, it is well known that COFs consist of over 100 types of hazardous compounds such as PM, PAHs, $NO_x$, and VOCs (S. Y. Cheng et al. 2016a, b; Ke et al. 2016; Lu et al. 2019; Peng et al. 2017; Yi et al. 2019; Zhu et al. 2001), which may exert an adverse impact on neurodevelopment (Brumberg & Karr 2021; Costa et al. 2019; Iqubal et al. 2020). For example, maternal exposure to PM and PAH during pregnancy through inhalation of COFs during cooking (Du et al. 2017; Hoseini et al. 2018) can enter into the fetus through the placenta barrier (Dong et al. 2018; Liu et al. 2021; Topinka et al. 2009). These substances then enter the central nervous system (CNS) via the olfactory bulb or via the blood–brain barrier (BBB) (Cipriani et al. 2018; Costa et al. 2017). When they arrive in the brain, these hazardous constituents can cause the release of proinflammatory mediators (e. g., interleukin (IL)-6, tumor necrosis factor (TNF)) leading to chronic respiratory and systemic inflammation (Rao et al. 2018; Totlandsdal et al. 2015; van Eeden et al. 2001), which injure the BBB and finally trigger neural-immune interaction and produce numerous reactive oxygen species (ROS) and chronic oxidative stress contributing to neuronal dysfunction (Calderon-Garciduenas et al. 2012, 2008). Furthermore, the enormous ROS can damage the BBB and change the permeability of the barrier (Block & Calderon-Garciduenas 2009; Heidari Nejad et al. 2015), which interfere with the neurodevelopment. They can also stimulate the release of vasoconstrictors such as catecholamines (Chiarella et al. 2014; Hajat et al. 2019). In addition,

the developing fetus lacks the immune response function and the ability to detoxify hazardous substances resulting in them being susceptible to the toxicity of air pollution (Anderson et al. 2000; Makri et al. 2004). Given the dearth of studies examining the mechanisms explaining the associations found in our study, more research is needed.

This study has several limitations that should be considered when interpreting the findings. First, it was a cross-sectional study, which limited our ability to interpret our findings as causal relationships. Second, all data in this study were collected in Longhua district in Shenzhen, which is one of the most developed regions in China. This may result in selection bias and restrict the generalizability of our findings to other areas of China. Third, the data were obtained retrospectively via self-report, thus, recall bias is possible. Fourth, the assessment of COFs exposure only relied on several questions from our questionnaire. However, COFs are produced in the processes of Chinese-cooking such as frying, roasting, grilling, boiling, and broiling, and are affected by combinations of ingredients, recipes and procedures, temperature, kitchen environment, and ventilation equipment (Zhang et al. 2010a, b). In addition, we did not collect information about the time spent cooking, the type of kitchen (separated or open plan), the processes of Chinese-cooking or ingredients used, the frequency of use of ventilation equipment during cooking, and the concentration of compounds of COFs indoors during cooking and in the outdoor air pollution. Moreover, it is possible that cooking behavior may change during the trimesters of pregnancy, which we did not measure. Thus, future research should adopt objective methods to assess these additional measures of exposure to COFs. Fifth, we did not collect information regarding family cooking habits during the first three years of the child's life. This would have allowed us to compare prenatal vs postnatal exposure to COFs upon the likelihood of the presence of autistic like behaviors in preschoolers. Finally, although, we controlled for many potential covariates, other variables that may affect the development of ASD, such as the parental psychiatric history, were not measured in this study.

## Conclusions

In summary, the findings from this study indicate that maternal cooking, resulting in COFs exposure, during pregnancy increases the likelihood of autistic-like behaviors in subsequent children, and that the use of clean fuels and ventilation measures can mitigate this risk of offspring's autistic-like behaviors. These results support a recommendation that pregnant women should avoid cooking using solid fuels, or use ventilation measures when they cook, to decrease the risk of poor neurobehavioral development in their offspring.

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**Author contribution** All authors contributed to the study conception and design. Jian-hui Yang involved in conceptualization, methodology, formal analysis, writing—original draft preparation, and writing—review and editing. Esben Strodl involved in methodology, writing—review and editing, and supervision. Chuan-An Wu involved in funding acquisition, methodology, investigation, project administration, and supervision. Xiang-Yu Hou involved in methodology, writing—review and editing, and supervision. Xiao-Na Yin involved in investigation, and project administration. Guo-Min Wen involved in investigation, and project administration. Deng-Li Sun involved in investigation, and project administration. Dan-Xia Xian involved in investigation, and project administration. Jing-Yi Chen involved in methodology, investigation, and project administration. Ying-Jie Chen involved in methodology, investigation, and project administration. Jing Chen involved in methodology, investigation, and project administration. Wei-Qing Chen involved in funding acquisition, project administration, conceptualization, methodology, writing—review, editing, and supervision.

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**Data availability** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

## Declarations

**Ethics approval** The study was approved by the Ethic Committee of School of Public Health of Sun Yat-sen University in Guangzhou, China (No. 2015–016). The study was conducted in accordance with the Declaration of Helsinki.2.2 Data collection. All the participants were informed of the aims and process of the study, gave informed consent, and participated deliberately in the study.

**Consent to participate** Before enrolling in the data gathering phase, all participants gave informed contest on participating in the research.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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