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Gas cooking indoors and respiratory symptoms in the ECRHS cohort

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ABSTRACT

Background: Gas cooking is an important source of indoor air pollutants, and there is some limited evidence that it might adversely be associated with respiratory health. Using repeated cross-sectional data from the multi-centre international European Community Respiratory Health Survey, we assessed whether adults using gas cookers have increased risk of respiratory symptoms compared to those using electric cookers and tested whether there was effect modification by *a priori* selected factors.

Methods: Data on respiratory symptoms and gas cooking were collected from participants at 26–55 and 38–67 years (median time between examinations 11.4 years) from interviewer-led questionnaires. Repeated

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associations between gas cooking (versus electric) and respiratory symptoms were estimated using multivariable mixed-effects logistic regression models adjusted for age, sex, study arm, smoking status, education level, and included random intercepts for participants within study centres. Analyses were repeated using a 3-level variable for type of cooker and gas source. Effect modification by ventilation habits, cooking duration, sex, age atopy, asthma, and study arm were examined.

Results: The sample included 4337 adults (43.7% males) from 19 centres in 9 countries. Gas cooking increased the risk of “shortness of breath whilst at rest” (OR = 1.38; 95%CI: 1.06–1.79) and “wheeze with breathlessness” (1.32; 1.00–1.74). For several other symptoms, effect estimates were larger in those who used both gas hobs and ovens, had a bottled gas source and cooked for over 60 min per day. Stratifying results by sex and age found stronger associations in females and younger adults.

Conclusion: This multi-centre international study, using repeat data, suggested using gas cookers in the home was more strongly associated than electric cookers with certain respiratory symptoms in adults. As gas cooking is common, these results may play an important role in population respiratory health.

1. Background

Urban residents spend over 90% of their time indoors or in enclosed spaces, and nearly two thirds of that time at home (Leech et al., 2002). Poor indoor air quality, which varies depending on pollutant sources and ventilation conditions, can lead to adverse health outcomes (Koivisto et al., 2019; Lewis et al., 2023; Vardoulakis et al., 2020). One common gaseous pollutant is nitrogen dioxide (NO_2), produced by indoor cooking stoves and heaters (Dennekamp, 2001; Willers et al., 2006). Gas is still the second most common fuel source used in Europe and North America, with more than a third of US households using a gas cooker in 2020 (US Energy Information Administration, 2020). It is therefore important to investigate any adverse health effects associated with the use of gas cooking indoors.

Several cross-sectional epidemiological studies have reported adverse respiratory health effects in children associated with indoor gas appliances and/or high NO_2 levels (Hölscher et al., 2000; Lin et al., 2013; Moshammer et al., 2010; Paulin et al., 2017). However, the epidemiological evidence on adults is more limited. A large cross-sectional multi-centre analysis of baseline data from the European Community Respiratory Health Survey (ECRHS) found some association between gas cooking and respiratory symptoms only in females, an effect that varied across centres (Jarvis et al., 1998). However, a smaller cross-sectional study of asthmatic adults found no association between gas cooking and respiratory symptoms (Eisner, 2003). One longitudinal study of adults found that gas cooking was associated with a reduction of FEV_1, but not with respiratory symptoms or asthma onset (Moran et al., 1999).

The conflicting evidence in adults may reflect that very few epidemiological studies have investigated how indoor air pollutants released during gas cooking vary by stove type, gas source, and ventilation practices during cooking, although it is known that ventilation habits predict indoor air quality and NO_2 concentrations (Lajoie et al., 2015; Vardoulakis et al., 2020). Sex and age have also been shown to act as effect modifiers for developing respiratory illness, with females and older individuals potentially at higher risk (Bentayeb et al., 2013; Leynaert et al., 1996; Triebner et al., 2016).

Large high-quality analyses that incorporate repeated data on domestic gas cooking behaviours and respiratory health outcomes, in addition to ventilation habits, are currently lacking. However, these are needed to understand whether long-term use of indoor gas cooking contributes to poor respiratory health in adults. The current analysis aimed to fill this gap by testing the hypothesis that using a gas cooker indoors, compared to using an electric cooker, increased the risk of respiratory symptoms in adults participating in the multi-centre ECRHS study (Burney et al., 1994; ECRHSII Steering Committee, 2002). Furthermore, we aimed to determine whether this association varied by gas cooker type, gas source, ventilation habits, cooking duration, sex, age, atopy, asthma and study arm.

2. Materials and methods

2.1. Study population

The ECRHS is a multi-centre cohort study of adults originally recruited in 1991–1993, from 56 centres across Europe and internationally. The study aimed to determine the incidence, prognosis, and risk factors of allergic and respiratory disease and has been described in detail elsewhere (Burney et al., 1994; ECRHSII Steering Committee, 2002). Briefly, for ECRHS I, adults aged 20–44 years were randomly selected from local sampling frames and sent a postal screening questionnaire. From those who responded, a random sample (population-based arm) and a group targeting asthmatics not selected in the random sample (symptomatic arm) were selected to undergo a more detailed clinical examination, which included an extended interviewer-led questionnaire and clinical tests.

Since this baseline assessment, two follow-ups (including questionnaires and clinical assessments) have taken place approximately ten years apart: ECRHS II in 1999–2003 and ECRHS III in 2010–2014. The present analysis primarily considers data from these last two assessments during which detailed information on cooking and ventilation behaviours was collected (not available in ECRHS I).

Ethical approval for the study was obtained from the local centre research ethics committee in each country and written consent was obtained from the subjects.

2.2. Gas cooking exposure at ECRHS II and III

At both ECRHS II and III, participants were asked “What kind of stove do you mostly use for cooking?” Participants were classified as using “electric” or “gas cookers” according to their answers, as detailed in the Supplementary Material. Those who used gas cookers were further divided into using: 1) only gas hobs, or 2) gas ovens ± gas hobs in a secondary analysis. Analyses were also repeated for gas cookers with gas coming from a “mains” versus a “bottled” (non-mains) source.

Centres with less than 5% of participants in the gas or electric cooker group were excluded due to lack of statistical power to compare associations. For the subgroup analyses, centres lacking statistical power in either subgroup (<5%) were excluded from that analysis only. Those who used other cooking fuel types (coal, coke or wood; paraffin, kerosene) were excluded, as there were very few participants (n = 8) and these fuels have been previously associated with respiratory symptoms (Sood, 2012).

Participants were asked about ventilation habits when cooking and were classified as using an extractor fan “sometimes/always use” or “never use”, and opening a door or window while cooking as “sometimes/always” or “never/none present”. Participants were asked “on average how long have you spent cooking with your stove each day over the last four weeks?” This was classified as cooking duration for <60 or ≥60 min, which corresponded approximately to the 75th percentile.

2.3. Respiratory outcomes

At both ECRHS II and III, participants were asked fourteen questions about experiencing respiratory symptoms in the last 12 months, including: wheezing, shortness of breath, cough, phlegm and nasal allergies. The present study analysed each question individually. The respiratory symptoms questions were taken from the bronchial symptoms questions of the International Union Against Tuberculosis and Lung Disease questionnaire (Burney and Chinn, 1987; Abramson et al., 1991), have been validated (Burney et al., 1989), and are the same at each ECRHS follow-up. Precise wording of the questions in English is detailed in the Supplementary Material, although each questionnaire is administered in the local language of the study centre.

2.4. Other relevant characteristics

Socio-demographic data included: age, sex (ECRHS I only), smoking status (never smoker; ex-smoker <15 pack-years; ex-smoker ≥15 pack-years; current smoker <15 pack-years; current smoker ≥15 pack-years), occupation (management; technicians; other non-manual; skilled manual; unskilled manual; unclassifiable/unknown) and age finished full-time education (<17; 17–20; >20 years, ECRHS II only). Height and weight were measured and used to calculate body mass index (BMI) at ECRHS II and III. Participants were categorised as underweight <18.5; normal 18.5–24.9; overweight 25–29.9; and obese ≥30 kg/m^2.

Blood samples were collected and tested for specific IgE to house-dust mites, cat, grass, *Cladosporium* using the Pharmacia CAP System. Participants were considered atopic if they had allergen-specific IgE levels equal to or above 0.35 kU$_A$/L for at least one of the four allergens tested at ECRHS II (Marcon et al., 2020).

Participants were classified as having a chronic respiratory disease if they self-reported having asthma or using inhaled medications in the last 12 months, or if they had COPD (defined as forced expiratory volume in the first second/forced vital capacity <0.70, from pre-bronchodilator spirometry values measured at ECRHS II and III (Bergqvist et al., 2020).

Home environment characteristics were self-reported by the participants at ECHRS II and III: presence of gas boiler, central heating, visible mould, house type (house; flat; other) and year of house construction (before/after 1981) (Jarvis et al., 1998).

2.5. Analysis

Associations between type of cooker (gas vs electric) and each respiratory symptom were estimated using multivariable mixed-effects logistic regression models with a random intercept for subjects nested within centres. Models were adjusted for smoking status (time-varying), age (time-varying), sex, education level and study arm (random or symptomatic). Analyses were repeated using a 3-level variable for type of cooker (gas hobs/gas hobs and ovens/electric) as well as fuel source (mains/bottled gas/electric).

Effect modification by ventilation (window or extractor fan use), average daily cooking duration, sex, age (stratified by the median), atopic status, asthma and study arm (symptomatic vs random sample) was assessed using interaction terms and stratified analyses based on data from ECRHS II.

In additional sensitivity analyses, we: 1) adjusted for other individual and sociodemographic factors (BMI; occupation; education) as well as housing characteristics (gas boiler; central heating; mould; house type; year house built) all in one model; 2) excluded participants with chronic respiratory diseases (having asthma, COPD, or using inhaled medication in the last 12 months, all at either ECRHS II or III); 3) repeated the main models without excluding centres with <5% of

Table 1
Demographics of study population at ECRHS II and ECRHS III.

Study Population	ECRHS II (N = 4230)		ECRHS III (N = 4169)		P Value[1]
Age, mean ± SD	42.5	±7.1	53.9	±7.1	<0.001
Females, n (%)	2232	52.8	2176	52.2	0.600
Cooker Type, n (%)					
Electric	2237	52.9	2609	62.6	
Gas	1993	47.1	1560	37.4	<0.001
Smoking, n (%)					
Never Smoked	1867	44.9	1888	49.0	
Ex Smoker <15 Pack Years	752	18.1	701	18.2	
Ex Smoker ≥15 Pack Years	430	10.4	586	15.2	
Current Smoker <15 Pack Years	448	10.8	186	4.8	
Current Smoker ≥15 Pack Years	659	15.9	493	12.8	<0.001
Sample, n (%)					
Random	3631	85.8	3577	85.8	0.959
Symptomatic	599	14.2	592	14.2	
Atopy, n (%)	1196	32.3	953	27.9	<0.001
Asthma, n (%)	676	15.6	808	18.7	<0.001
Chronic obstructive pulmonary disease, n (%)	227	6.1	559	15.4	<0.001
Use of inhaled medication in last 12 months, n (%)	533	12.3	619	15.9	<0.001
Body Mass Index, n (%)					
Underweight <18.5 kg/m^2	51	1.3	21	0.5	
Normal 18.5–24.9 kg/m^2	1827	47.8	1331	34.3	
Overweight 25–29.9 kg/m^2	1408	36.8	1546	39.8	
Obese ≥30 kg/m^2	539	14.1	985	25.4	<0.001
Age Finished Education, n (%)					
<17 Years	843	21.0			
17–20 Years	1044	26.0			
>20 Years	2136	53.1			
Occupation, n (%)					
Management/Professionals	1450	33.4	1525	35.2	
Technicians/Associates	704	16.2	726	16.7	
Other Non-Manual	1001	23.1	905	20.9	
Skilled manual	390	9.0	344	7.9	
Semi/Unskilled manual	375	8.7	366	8.4	
Unclassifiable/Unknown	417	9.6	471	10.9	0.064

[1] Comparisons between populations at ECRHS II and III performed using the chi-square test or one-way ANOVA for categorial variables, and Student's t-test for continuous variables.

Table 2
Cooking behaviours and indoor housing characteristics of gas and electric cooking users at ECRHS II.

Characteristics		Electric (N = 2237)		Gas (N = 1993)		P Value[1]
		n	%	n	%	
Window/Door Opening	Sometimes/Always	1349	70.3	1135	73.9	
	Rarely/Never	571	29.7	401	26.1	0.018
	Missing	317		457		
Fan Use Frequency	Sometimes/Always	1611	72.6	1299	65.7	
	Never	607	27.4	677	34.3	<0.001
	Missing	19		17		
Average Daily Cooking Duration	<60 min	1562	71.8	1108	63.8	
	≥60 min	615	28.3	628	36.2	<0.001
	Missing	60		257		
Gas Boiler Present		621	32.5	1109	58.7	<0.001
	Missing	326		102		
Central Heating Present		1716	76.7	1210	60.8	<0.001
	Missing	0		3		
Mould Present		527	23.6	643	32.4	<0.001
	Missing	6		10		
House Type	House	508	22.7	518	26.0	
	Flat	754	33.7	480	24.1	
	Other	975	43.6	995	49.9	0.241
House Built Before 1981		1299	60.7	1338	78.9	
	Missing	98		296		<0.001
Age (mean ± SD)		42.5	±7.2	42.5	±7.0	0.561
Sex	Females	1175	52.5	1057	53.0	0.74
Smoking	Never Smoked	950	44.8	873	45.1	
	Ex Smoker <15 Pack Years	398	18.8	337	17.4	
	Ex Smoker ≥15 Pack Years	231	10.9	196	10.1	
	Current Smoker <15 Pack Years	226	10.7	208	10.8	
	Current Smoker ≥15 Pack Years	316	14.9	320	16.6	0.234
Sample	Random	1945	87.0	1686	84.6	
	Symptomatic	292	13.1	307	15.4	0.029
Atopy		610	30.4	574	34.6	0.007
Asthma		333	14.9	337	16.9	0.072
Chronic obstructive pulmonary disease		117	5.9	110	6.6	0.393
Use of inhaled medication in last 12 months		247	11.0	275	13.8	0.006
Body Mass Index	Underweight <18.5 kg/m^2	22	1.1	29	1.7	
	Normal 18.5–24.9 kg/m^2	984	47.9	824	47.7	
	Overweight 25–29.9 kg/m^2	760	37.0	631	36.6	
	Obese ≥30 kg/m^2	289	14.1	242	14.0	0.563
Age Finished Education	<17 Years	354	16.3	455	26.1	
	17–20 Years	613	28.2	403	23.1	
	>20 Years	1210	55.6	886	50.8	<0.001
Occupation	Management/Professionals	731	32.7	709	35.6	
	Technicians/Associates	378	16.9	318	16.0	
	Other Non-Manual	568	25.4	419	21.0	
	Skilled Manual	200	8.9	181	9.1	
	Semi/Unskilled Manual	177	7.9	183	9.2	
	Unclassifiable/Unknown	183	8.2	183	9.2	0.027

[1] Comparisons between electric and gas cooking users performed using the chi-square test or one-way ANOVA for categorial variables, and Student's t-test for continuous variables.

participants in the gas or electric cooker groups.

All analysis were carried out using the statistical program STATA V.17 (StataCorp, College Station, TX). Figures were created with Graphpad Prism 9.3.0 (GraphPad Software, San Diego, California USA, www.graphpad.com).

3. Results

3.1. Study population

There were 10,933 participants in ECRHS II from 29 centres in 14 countries. The following participants were excluded: those who did not participate in ECRHS III (n = 5032), seven centres lacking statistical power in either cooker group (n = 1556; further detailed in Supplementary Material) and eight participants using other fuel types at both surveys. The final study population was 4337 participants from 19 centres in 9 countries, who contributed 4230 observations at ECRHS II and 4169 observations at ECRHS III (flow chart in Supplementary Fig. S1).

Demographic data of the 4337 study participants are presented in Table 1. The median follow-up time between ECRHS II and III was 11 years 5 months (25th centile = 10.5 years; 75th centile = 12.2 years). The age of participants ranged from 26 to 55 years (mean 42.5 years) and 38–67 years (mean 53.9 years) at ECRHS II and III respectively. At both surveys, most participants reported never smoking, and current smokers were slightly younger than ex- and never smokers (mean ages at ECRHS II: current smokers 41.1, ex-smokers 44.5, never smoked 42.1 years). Compared to those excluded, subjects included in the analysis were slightly older, more likely to use a gas stove, be from the random sample, and have a non-manual occupation, but less likely to have a chronic respiratory disease (Supplementary Table S1).

3.2. Prevalence of gas cooking and respiratory symptoms

Overall, the prevalence of gas cooking was 47.1% and 37.4% at ECRHS II and III, respectively. This varied substantially across centres, from 7.2% in Reykjavik to >80% in Melbourne and Barcelona at ECRHS II (Supplementary Table S2). Gas cooking prevalence decreased in most

Table 3
Odds ratios (OR) for gas cooking and respiratory symptoms.

Symptoms In The Last 12 Months	Unadjusted OR			Adjusted OR[1]			Additionally Adjusted (Sensitivity Analysis)[2]		
	OR	95% CI		OR	95% CI		OR	95% CI	
Wheezing And Whistling In Chest	1.16	1.05	1.28	1.15	0.92	1.43	1.23	0.97	1.57
Wheeze With Breathlessness	1.25	1.10	1.42	**1.32**	**1.00**	**1.74**	1.33	0.99	1.77
Wheeze With No Cold	1.06	0.94	1.20	1.03	0.79	1.34	1.11	0.83	1.48
Woken Up With A Feeling Of Chest Tightness	1.23	1.10	1.39	1.15	0.93	1.42	1.19	0.95	1.48
Shortness Of Breath Whilst At Rest	1.26	1.08	1.47	**1.38**	**1.06**	**1.79**	**1.55**	**1.17**	**2.06**
Shortness Of Breath After Activity	1.23	1.12	1.37	1.11	0.92	1.35	1.10	0.90	1.34
Woken By Shortness Of Breath	0.99	0.85	1.16	0.87	0.67	1.15	0.96	0.71	1.28
Woken By Attack Of Coughing	1.12	1.02	1.23	0.97	0.82	1.15	0.98	0.82	1.18
Cough During Winter	1.11	0.98	1.25	1.18	0.94	1.49	1.21	0.94	1.55
Cough Up To 3 Months Each Year	1.12	0.97	1.31	1.19	0.91	1.56	1.19	0.89	1.58
Phlegm In The Morning In Winter	1.04	0.92	1.18	1.18	0.91	1.53	1.22	0.92	1.61
Phlegm Day Or Night In Winter	1.04	0.90	1.19	1.09	0.85	1.40	1.13	0.86	1.49
Phlegm Up To 3 Months Each Year	0.99	0.83	1.17	1.01	0.76	1.33	1.02	0.76	1.37
Any Nasal Allergies Including Hay Fever	1.21	1.10	1.33	1.06	0.82	1.38	1.11	0.83	1.50

[1] Odds ratios and 95% confidence intervals generated from mixed effects logistic regression. Compares using gas cookers to electric cookers. Models adjusted for age, sex, smoking, sample type, age finished education and include a random intercept for subjects nested within centres (n = 4337).

[2] Odds ratios and 95% confidence intervals generated from mixed effects logistic regression. Compares using gas cookers to electric cookers. Models adjusted for age, sex, smoking, sample type, age finished education and include a random intercept for subjects nested within centres, and also the following socio-demographic and indoor characteristics: BMI, occupation, year house built, house type, central heating and mould presence in the home (n = 3145).

Table 4
Odds ratios (OR) for gas cooker type and respiratory symptoms[1].

Symptoms In The Last 12 Months	Gas Hob			Gas Oven ± Hob		
	OR	95% CI		OR	95% CI	
Wheezing And Whistling In Chest	1.10	0.84	1.43	**1.55**	**1.11**	**2.16**
Wheeze With Breathlessness	1.22	0.89	1.68	**1.53**	**1.02**	**2.29**
Wheeze With No Cold	1.10	0.81	1.50	1.21	0.82	1.81
Woken Up With A Feeling Of Chest Tightness	1.13	0.89	1.44	1.25	0.92	1.70
Shortness Of Breath Whilst At Rest	1.26	0.92	1.72	**1.61**	**1.09**	**2.38**
Shortness Of Breath After Activity	1.10	0.89	1.37	1.15	0.87	1.52
Woken By Shortness Of Breath	0.81	0.59	1.10	0.71	0.46	1.08
Woken By Attack Of Coughing	1.03	0.85	1.25	0.95	0.73	1.22
Cough During Winter	1.15	0.88	1.52	**1.62**	**1.16**	**2.26**
Cough Up To 3 Months Each Year	1.21	0.87	1.67	1.44	0.97	2.14
Phlegm In The Morning In Winter	1.06	0.78	1.46	**1.54**	**1.04**	**2.28**
Phlegm Day Or Night In Winter	0.89	0.66	1.22	**1.70**	**1.17**	**2.46**
Phlegm Up To 3 Months Each Year	0.96	0.68	1.33	1.31	0.86	1.99
Any Nasal Allergies Including Hay Fever	1.06	0.78	1.43	1.21	0.82	1.79

[1]Odds ratio and 95% confidence intervals generated from mixed-effects logistic regression, with a three-level exposure variable for gas stove type (electric cooker/gas hob/gas oven) with electric cooker as the reference category (OR = 1.0). Models adjusted for age, sex, smoking, sample type, age finished education and include a random intercept for subjects nested within centres.

Table 5
Odds ratios (OR) for gas source type and respiratory symptoms[1].

Symptoms In The Last 12 Months	Mains Gas			Bottled Gas		
	OR	95% CI		OR	95% CI	
Wheezing And Whistling In Chest	0.98	0.74	1.30	**1.65**	**1.18**	**2.31**
Wheeze With Breathlessness	1.23	0.87	1.73	**1.74**	**1.15**	**2.65**
Wheeze With No Cold	0.90	0.65	1.25	1.36	0.92	2.03
Woken Up With A Feeling Of Chest Tightness	1.10	0.85	1.43	1.30	0.94	1.80
Shortness Of Breath Whilst At Rest	1.35	0.97	1.89	1.36	0.90	2.07
Shortness Of Breath After Activity	1.10	0.85	1.41	1.06	0.78	1.44
Woken By Shortness Of Breath	0.81	0.57	1.14	1.02	0.67	1.53
Woken By Attack Of Coughing	0.94	0.76	1.16	0.99	0.76	1.29
Cough During Winter	1.11	0.81	1.51	1.05	0.73	1.53
Cough Up To 3 Months Each Year	1.07	0.74	1.53	1.35	0.90	2.03
Phlegm In The Morning In Winter	1.10	0.78	1.57	1.15	0.76	1.72
Phlegm Day Or Night In Winter	0.88	0.63	1.23	1.22	0.83	1.80
Phlegm Up To 3 Months Each Year	0.84	0.58	1.21	1.18	0.78	1.78
Any Nasal Allergies Including Hay Fever	1.05	0.75	1.46	1.00	0.66	1.51

[1]Odds ratio and 95% confidence intervals generated from mixed-effects logistic regression, with a three-level exposure variable for gas source type (electric cooker/mains gas/bottled gas), with electric cooker as the reference category (OR = 1.0). Models adjusted for age, sex, smoking, sample type, age finished education and include a random intercept for subjects nested within centres.

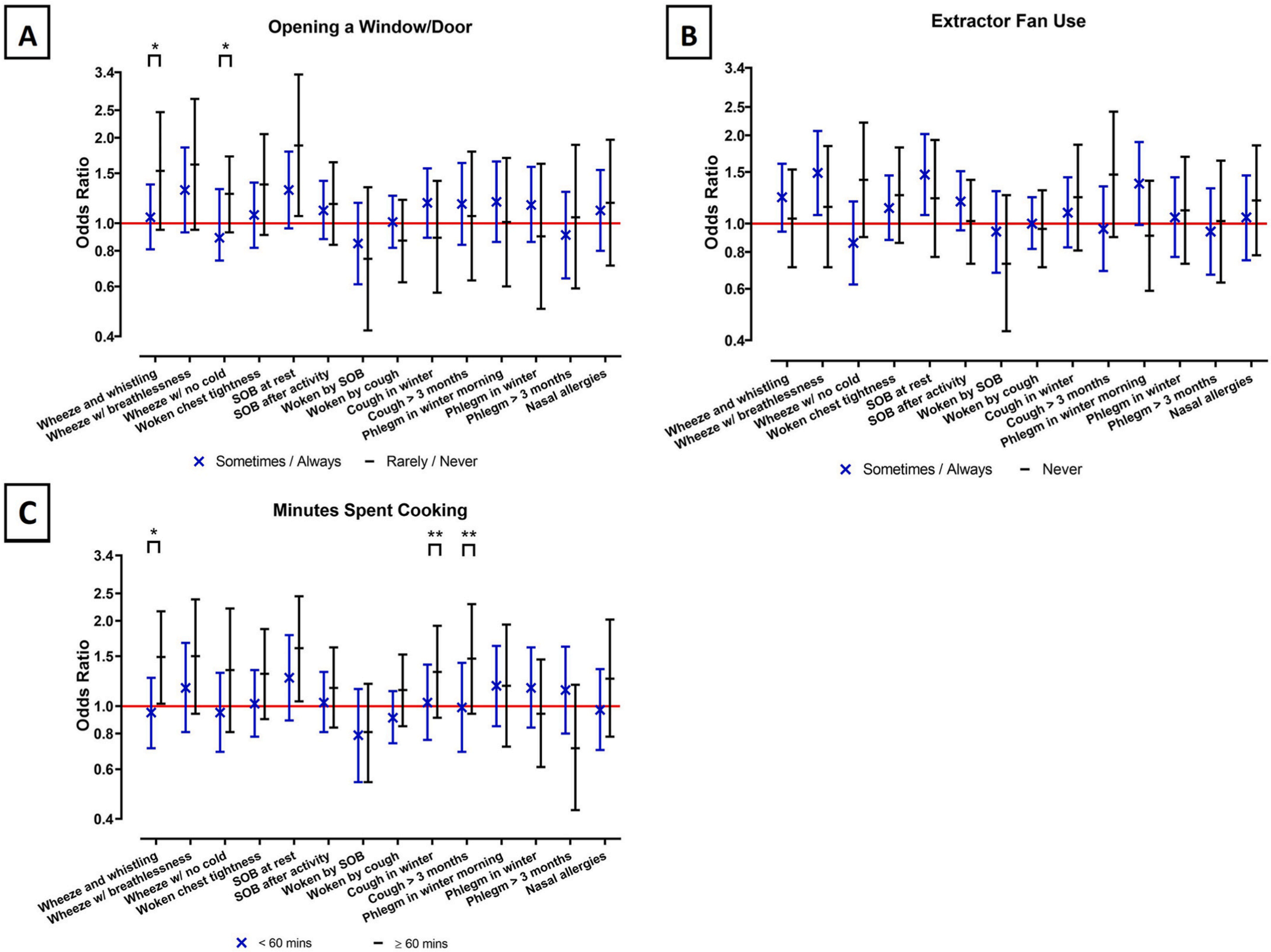

Fig. 1. *Repeat associations between gas cookers and respiratory symptoms stratified by ventilation habits (window/door (A), using an extractor fan (B); and minutes spent cooking per day (C); according to ECRHS II data.* Odds ratio and 95% confidence intervals generated from mixed-effects logistic regression, comparing gas cookers to electric cookers. Models adjusted for age, sex, smoking, age finished education, sample type and include a random intercept for subjects nested within centres.
SOB = Short of Breath
Key = Ventilation habits (A/B): (X)sometimes/always (−)rarely/never, minutes spent cooking per day (C): (X) < 60 min/(−)≥60 min
* p-interaction term <0.1 ** p-interaction term <0.05.

centres between the two surveys, apart from Montpellier, Norwich, Reykjavik and Melbourne, where the prevalence increased. Of those who used gas at ECRHS III, 85.2% also used gas at ECRHS II. At both follow-ups, gas cooking participants were more likely to use a gas hob only and have a mains gas source.

There were several differences in terms of cooking behaviours, indoor housing characteristics and individual characteristics (as assessed at ECRHS II) between gas versus electric cooking users (Table 2). Users of gas cookers were more likely to have a gas boiler, mould present, live in an older house, not use ventilation when cooking and cook for a longer duration compared to those with electric cookers. They were also more likely to be from the symptomatic sample, have asthma, use inhaled medications, be atopic, and have a manual occupation. However, they had fewer years of education and were less likely to have central heating. Several differences in characteries were also identified when comparing gas cooking subgroups (Supplementary Table S3 for electric/gas hob only/gas oven and hob and Table S4 for electric/mains gas/bottled gas). Notably, there was no significant difference in cooking duration between those using only gas hobs or gas ovens ± hobs at either survey (mean duration 59.9 min vs. 56.4 min at ECRHS II, and 49.1 min vs. 52.7 min at ECRHS III).

The prevalence of respiratory symptoms in the last 12 months is shown in Supplementary Table S5. The most common symptom was "nasal allergies" followed by "woken by attack of coughing" in both surveys. There was no significant difference in the prevalence of respiratory symptoms between the surveys, apart from nasal allergies and cough in winter, which increased.

3.3. Associations between gas cookers and respiratory symptoms

Using gas cookers, compared to using electric cookers, was associated with increased risk of "shortness of breath whilst at rest" (OR = 1.38; 95%CI: 1.06–1.79; Table 3), and "wheeze with breathlessness" (1.32; 1.00–1.74) in adjusted models. Effect estimates for wheezing and whistling, waking up feeling chest tightness, shortness of breath after activity, cough during winter, cough >3 months and phlegm in the morning in winter were also elevated but confidence intervals crossed 1.0. Unadjusted odds ratios are also displayed in Table 3.

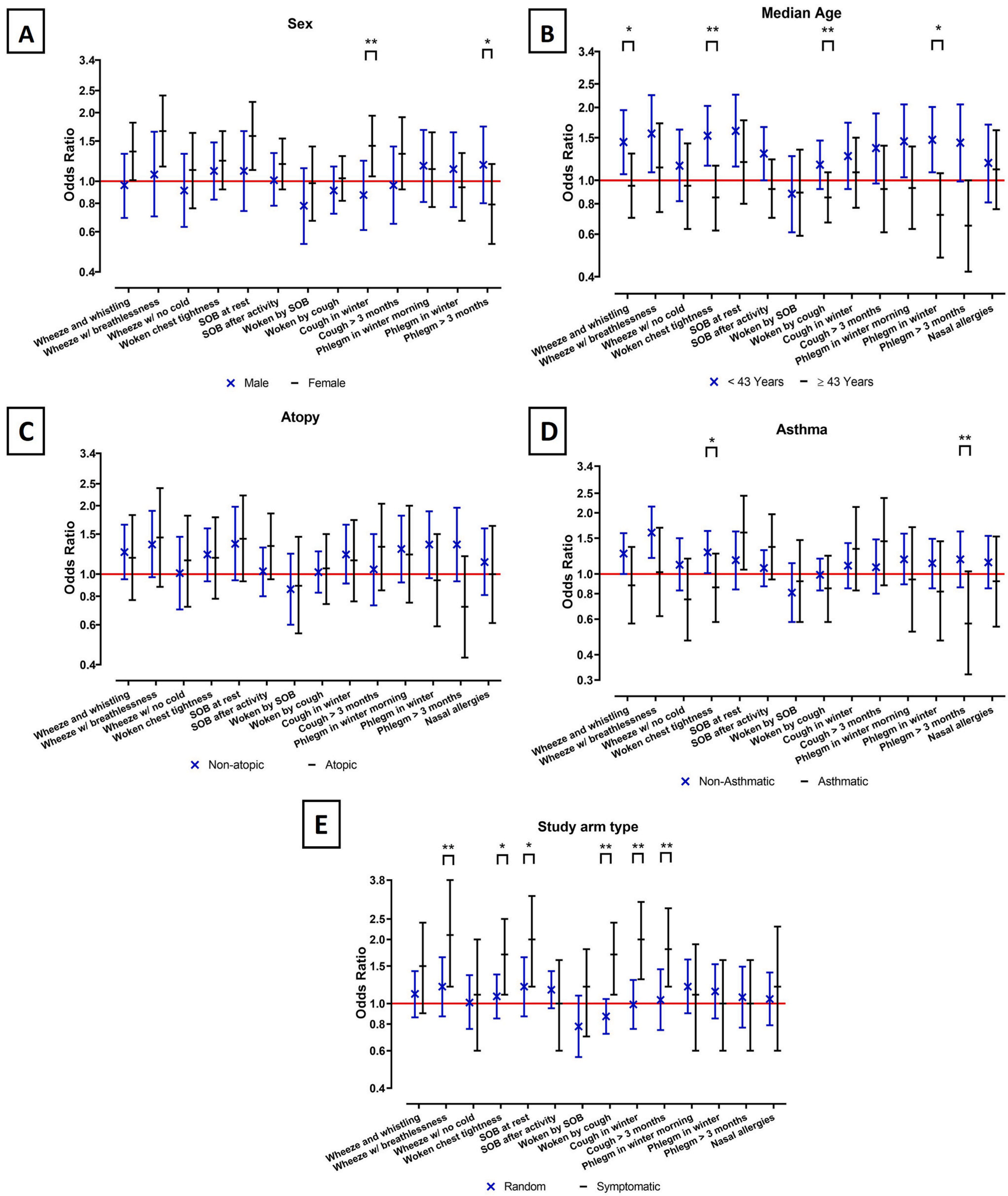

Fig. 2. *Repeat associations between gas cookers and respiratory symptoms stratified by sex (A); median age (B); atopy (C); asthma (D); and study arm (E); according to ECRHS II data.* Odds ratio and 95% confidence intervals generated from mixed-effects logistic regression, comparing gas cookers to electric cookers. Models adjusted for age, sex, smoking, age finished education, sample type and include a random intercept for subjects nested within centres. Models stratified by sex are not adjusted for sex, stratified by age are not adjusted for age, and stratified by sample type are not adjusted for sample type. The model for nasal allergies in Fig. 2A did not converge.
SOB = Short of Breath
Key = Sex (A): (X)male/(−)female, median age (B): (X) < 43 years/(−)≥43 years, atopy (C): (X)non-atopic/(−) atopic, asthma (D): (X)non-asthmatic/(−) asthmatic, study arm (E): (X)random/(−)symtomatic
* p-interaction term <0.1 ** p-interaction term <0.05.

When gas cookers were further classified as gas hob only versus gas oven ± gas hob, and compared to electric cookers, associations were notably stronger for those with a gas oven, especially for wheezing and whistling, wheeze with breathlessness, shortness of breath at rest, cough and phlegm during winter. There were no significant associations among those only using gas hobs when compared to electric cookers (Table 4).

Similarly, analyses in which gas cookers were classified by source of gas (mains versus bottled) indicated stronger associations for several symptoms among those using bottled gas and no associations among those using gas from mains (Table 5).

3.4. Effect modification by ventilation, daily cooking duration, sex, age, atopy, asthma and study arm

Associations with gas cookers in general (including hobs, ovens and all gas sources) were stronger for some symptoms among those who rarely/never opened a window or door compared to those who did (Fig. 1A). Associations differed less with extractor fan usage (Fig. 1B). All interaction terms between ventilation (window/door or fan) and gas cooking were non-significant (p-interaction >0.05). When using less stringent criteria (p-interaction <0.1), a difference was observed between "wheezing and whistling" (p-int = 0.088) and "wheeze with no cold" (p-int = 0.091) for opening a window/door.

Associations appeared stronger for nearly all respiratory symptoms among those who spent 60 min or more cooking per day, compared to those who spent less than 60 min (Fig. 1C), and interaction terms were significant for "wheezing and whistling" (p-int = 0.059) "cough in winter" (p-int = 0.03) and "cough >3 months" (p-int = 0.05).

Stratifying associations by sex showed females were at greater risk for several respiratory symptoms associated with gas cooking (Fig. 2A), although there was only interaction between sex and gas cooking for "cough in winter" (p-int = 0.012). An exception to this trend was observed for the "phlegm" symptoms, with males appearing at greater risk, in particular "phlegm for >3 months" (p-int = 0.096). Models restricted to females further stratified by average daily cooking duration yielded greater effect estimates for several symptoms among those who cooked for 60 min or more (Supplementary Fig. S2).

Stratifying associations by median age at ECRHS II suggested those younger were at greater risk for nearly all respiratory symptoms (Fig. 2B), with interactions observed for "wheezing and whistling" (p-int = 0.081), "woken with chest tightness" (p-int = 0.015), "woken by cough" (p-int = 0.044) and "phlegm in winter" (p-int = 0.053).

Individuals with atopy (Fig. 2C) and asthma (Fig. 2D) were not identified as at-risk groups. In fact for "woken with chest tightness" and "phlegm for >3 months" associations appeared stronger among those without asthma (p-int = 0.073 and 0.033, respectively).

Finally, associations were notably stronger in the symptomatic study arm of the ECRHS for several symptoms (Fig. 2E), with interactions identified for "wheeze with breathlessness" (p-int = 0.036), "woken with chest tightness" (p-int = 0.083), "shortness of breath at rest" (p-int = 0.089), "woken by cough" (p-int = 0.005), "cough in winter" (p-int = 0.003) and "cough >3 months" (p-int = 0.019). Although overall associations tended to the null in the random study arm when comparing electric vs gas cookers (Fig. 2E), those with poor ventilation habits or who cooked for ≥60 min (Supplementary Fig. S3), as well as those who used a gas oven and hob (Supplementary Table S6) and bottle gas (Supplementary Table S7) were still observed to be at increased risk of respiratory symptoms in the random sample.

3.5. Sensitivity analysis

Adjusting for other socio-demographic and home characteristics (BMI, education, occupation, home type, home age, mould, gas boiler, central heating; all applied in one model) restricted the sample size to 3145 participants but did not affect the adjusted associations reported in Table 3. Additionally, repeating the analyses without excluding the seven centres with <5% of participants in the gas or electric cooker group (n = 5885; Supplementary Table S8) or excluding those with chronic respiratory disease (n = 3523; Supplementary Table S8) both resulted in similar trends as the main model, although confidence intervals were wider.

4. Discussion

Adults using gas for cooking were found to be more likely to self-report respiratory symptoms, compared to those using electric cookers, using data from various European countries collected twice over a period of 11 years. Gas cooking was consistently associated with an "attack of shortness of breath whilst at rest", with weaker associations observed for several other symptoms. This study is the first to analyse gas cooking methods in detail, testing interactions with indoor ventilation, cooking duration, sex, age, atopy and asthma. The risk was greater among those using both gas ovens and hobs, those who have a bottled gas source, those who ventilated less and those who cooked for longer durations. These findings suggest an exposure-response effect with higher risk related to higher underlying exposure levels.

Gas cooking is an important determinant of indoor NO_2 concentrations, followed by ventilation and outdoor NO_2 levels (Cyrys et al., 2000; Lambert et al., 1993; Vardoulakis et al., 2020). NO_2 is produced from incomplete combustion during cooking, and measured average indoor NO_2 concentrations are significantly higher in homes with a gas cooker compared to electric (Kornartit et al., 2010), as are other indoor air pollutants (Dennekamp, 2001; Kornartit et al., 2010). These air pollutants are inhaled, leading to oxidative stress and pulmonary inflammation, with potential to accumulate in peripheral organs (Briggs, 2003; Konduracka and Rostoff, 2022; Ohlwein et al., 2019; Paital and Agrawal, 2021). There is thus a clear biological pathway by which pollutants produced from gas cooking may cause respiratory symptoms, consistent with our findings.

Previous studies have found that duration of gas cooking is associated with NO_2 concentrations in an exposure-dependent fashion, supporting our observation of stronger associations for those who cook for longer (Paulin et al., 2017). This may partly explain the stronger associations we found among participants with both gas ovens and gas hobs, as cooking with an oven often requires a longer duration than with hobs (Dennekamp, 2001). Although our study did not show a difference in cooking duration between gas hob and oven users, other ECRHS studies have found that gas ovens were the only domestic gas appliance associated with high household levels of NO_2 in Italy (Ponzio et al., 2006). Demonstrating that cooking duration supports an exposure-response relationship is an important step towards establishing causality.

Our results also show stronger associations for those who used bottled gas, rather than a mains source. Bottled gas often involves user-replaced cylinders, which are susceptible to leaks or accidents, as opposed to permanent gas pipelines (Paliwal G et al., 2022). Unfortunately, we did not have information on whether the bottled gas cylinders were stored inside or outside the home. Another reason could be other social factors associated with bottled gas households, which were more common in Spain and Iceland. Compared to participants with mains gas, those using bottled gas were more likely to be less educated and have visible mould indoors, although adjusting our models for these factors did not change the main findings.

Characteristics of kitchens and human behaviour influence the concentration of built-up indoor gases, such as using an extractor fan or opening a window (Kornartit et al., 2010). Those who rarely opened a door or window were at greater risk of respiratory symptoms. This is consistent with literature on indoor cooking and poor ventilation (Lajoie et al., 2015; Lambert et al., 1993; Vardoulakis et al., 2020; Willers et al., 2006). Our results were less consistent for extractor fan use, although the efficiency of extractor fans in removing indoor air pollutants can vary widely and is likely to be less than advertised (Singer et al., 2012).

Females using gas cookers may be at greater risk of reporting symptoms than males, especially those who cooked for a longer duration. This follows previous cross-sectional results demonstrated by Jarvis et al. using data from ECRHS I (Jarvis et al., 1998). Similar results were also replicated in the French ECRHS centres, which showed associations with chronic bronchitis (Leynaert et al., 1996). Women reported cooking for longer than men, which may explain the stronger associations seen in females due to increased exposure to gas cooking. Biological sex differences in susceptibility to indoor pollutants on respiratory health may also exist (Svanes et al., 2018; Triebner et al., 2016).

Younger adults using gas cookers appeared to be at greater risk of respiratory symptoms in our study. This does not support the existence of a long-term exposure-response relationship and contrasts with other studies suggesting older adults are at greater risk (Triebner et al., 2016). There were some differences in characteristics between the two age groups which could be investigated in future research. For example, current smoking was more prevalent among the younger participants, which might have placed then at higher risk, although all models were adjusted for age and smoking status.

Asthma and atopy were also investigated as effect modifiers, however we found no evidence to suggest these were at-risk groups. Associations were however notably stronger in the symptomatic arm of the ECRHS study, suggesting that those with pre-existing respiratory symptoms were more susceptible to the adverse effects of indoor gas cooking. However, it is important to note that the adverse associations observed among those with suspected greater exposure to gas (poor ventilation habits, longer cooking duration times, using a gas hob and oven and having a bottled gas source) were nonetheless observed in the random population-study arm of the ECRHS (symptomatic sample excluded), highlighting the potential for indoor air pollutants to exacerbate respiratory health symptoms in the general population.

Important strengths of this study were the repeated data collection from the same population at two separate time points, approximately eleven years apart, which allowed us to better establish the sequence of events and causality. This improves upon previous similar research, often based on smaller populations in cross-sectional analyses (Eisner, 2003; Hölscher et al., 2000; Paulin et al., 2017; Wong, 2004). Further, the international multi-centre design of the ECRHS increases external validity. Only two international studies exist, both of which are based on cross-sectional ECRHS data, and showed associations between gas cooking with increased respiratory symptoms and bronchial responsiveness (Amaral et al., 2014; Jarvis et al., 1998).

Detailed data collected within ECRHS allowed us to examine many potential confounding factors in sensitivity analyses. For example, gas cookers were more likely to be found in older houses, which often have other characteristics that negatively influence indoor air quality, such as mould (Casas et al., 2012). Adjusting for these characteristics did not alter our conclusions.

In this study, participants were classified as gas or electric cooker users based on an interviewer-led questionnaire, although true individual exposures within these groups could vary widely. Indeed, a limitation of this work is that we did not have any direct measurements of indoor pollutants (e.g. NO_2) within the home. We tried to address this by analysing cooking duration, although cooking habits have been shown to change with seasonal variation, with less cooking occurring during the summer months (Tarlo et al., 2010). This could have led to some likely non-differential misclassification (leading to a lower observed effect than the true effect) and increasing variability in our exposure-outcome associations, the latter of which would lead to wider confidence intervals and thus a reduced ability to observe statistically significant results. Furthermore, we did not record the duration or frequency participants cooked with either a gas hob or oven, but only the combined value. More detailed questions of cooking behaviour could determine if there was a specific cooking method that placed people at particular risk, and whether seasonal changes play a role. Further, as we did not collect information on the proportion of time other household members also cooked, it was not possible for us to identify whether the study participant was the primary cook in the household or to what extent others might contribute to cooking-related exposures in the home.

As with all repeated data collected from participant questionnaires over a long period of time, there was a risk of loss-to-follow-up and selection bias. A previous analysis of this issue, which included ECRHS data, suggests that exposure-outcome associations appear mainly unchanged by loss to follow-up, which provides confidence in our ability to identify valid associations between risk factors and respiratory health (Johannessen et al., 2014). A further limitation is that for some stratified and interaction analyses, we had small numbers of participants within some centres. This might explain the lack of formal statistical significance observed for several of the comparisons conducted. Finally, it is possible that some of the observed associations may be chance findings due to the number of associations tested throughout the analyses, although analyses were decided upon *a priori* and based on prior knowledge and hypotheses.

5. Conclusions

Our findings, based on a multi-centre cohort of adults, suggest that using gas cookers in the home was more strongly associated with the risk of certain respiratory symptoms, compared to using electric cookers. Associations were greatest for those who used both a gas oven and hob, whose gas was supplied from a bottled source, those who ventilated less and who spent more than 60 min a day cooking, all of which may reflect increased indoor NO_2 exposure in the home. This study provides observational evidence of an adverse effect of gas cooking on respiratory health, and suggests it is urgent to establish a potential causal relationship.

CRediT authorship contribution statement

Holly Pan: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Debbie Jarvis:** Conceptualization, Data curation, Funding acquisition, Resources, Writing – review & editing, Methodology. **James Potts:** Data curation, Resources, Writing – review & editing, Methodology. **Lidia Casas:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Dennis Nowak:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Joachim Heinrich:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Judith Garcia Aymerich:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Isabel Urrutia:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Jesus Martinez-Moratalla:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **José-Antonio Gullón:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Antonio Pereira-Vega:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Chantal Raherison:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Sebastien Chanoine:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Pascal Demoly:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Bénédicte Leynaert:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Thorarinn Gislason:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Nicole Probst:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Michael J. Abramson:** Data curation, Funding acquisition, Methodology,

Resources, Writing – review & editing. **Rain Jõgi:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Dan Norbäck:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Torben Sigsgaard:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Mario Olivieri:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Cecilie Svanes:** Data curation, Funding acquisition, Methodology, Resources, Writing – review & editing. **Elaine Fuertes:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2023.114310.

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