

## ORIGINAL ARTICLE

## Prenatal fever and autism risk

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Some studies suggest that prenatal infection increases risk of autism spectrum disorders (ASDs). This study was undertaken in a prospective cohort in Norway to examine whether we could find evidence to support an association of the prenatal occurrence of fever, a common manifestation of infection, with ASD risk. Prospective questionnaires provided maternal exposure data; case status was established from clinical assessments and registry linkages. In a large, prospectively ascertained cohort of pregnant mothers and their offspring, we examined infants born  $\geq 32$  weeks for associations between fever exposure in each trimester and ASD risk using logistic regression. Maternal exposure to second-trimester fever was associated with increased ASD risk, adjusting for presence of fever in other trimesters and confounders (adjusted odds ratio (aOR), 1.40; 95% confidence interval, 1.09–1.79), with a similar, but nonsignificant, point estimate in the first trimester. Risk increased markedly with exposure to three or more fever episodes after 12 weeks' gestation (aOR, 3.12; 1.28–7.63). ASD risk appears to increase with maternal fever, particularly in the second trimester. Risk magnified dose dependently with exposure to multiple fevers after 12 weeks' gestation. Our findings support a role for gestational maternal infection and innate immune responses to infection in the pathogenesis of at least some cases of ASD.

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## INTRODUCTION

Autism spectrum disorders (ASD) are associated with prenatal exposure to a wide range of infectious agents.<sup>1–4</sup> The diversity of potential infectious triggers suggests that host factors, such as activation of maternal immunity, may have a role in the genesis of neurodevelopmental consequences.<sup>5</sup> Consistent with this concept, some studies have demonstrated higher levels of inflammatory cytokines in amniotic fluid<sup>6</sup> or maternal mid-gestational serum.<sup>7</sup> Maternal responses to infection, therefore, including the timing of fever episodes relative to fetal brain development and measures to mitigate fever, may influence risk of ASD.<sup>8,9</sup>

Maternal fever is common in pregnancy. Twenty percent of pregnant US women report one or more fever episodes.<sup>10</sup> Primarily (though not exclusively) first-trimester fever episodes have been linked to severe brain damage and structural anomalies.<sup>9,11</sup> Although first-trimester exposure may also influence subsequent more subtle disruptions of brain development, some investigators have hypothesized that exposure to fever later in pregnancy should be more strongly related to more subtle disruptions—including effects on neuronal migration,<sup>12</sup> proliferation<sup>12,13</sup> and myelination<sup>14</sup>—such as those reported in some studies of ASD.<sup>15–19</sup> Few studies have examined the association of prenatal fever, *per se*, with autism outcomes, as opposed to effects of specific types of maternal infection (for example, influenza). Fever was associated with a 1.4-fold increased risk of infantile autism in a prospective Danish cohort study wherein fever reporting was restricted to the first 32 weeks of gestation.<sup>20</sup> Fever persisting for 7 days or more was associated with a 1.6-fold increased risk for ASD and greater than threefold

increase in risk for infantile autism. A retrospective case–control study in the US found a twofold increased risk of ASD or another developmental disorder with prenatal fever; risk was lower in mothers treated with antipyretics.<sup>21</sup> However, no prospective studies have examined risk after fever across all of pregnancy or in conjunction with antipyretic use. In addition, prior work has not examined the possibility that different classes of antipyretics may differentially influence fever risk through their distinct biological effects. These include acetaminophen, an antipyretic with minimal anti-inflammatory effects that is used by over 50% of women in both Scandinavia<sup>22</sup> and the US<sup>23</sup> at least once during pregnancy that also affects oxidative stress,<sup>24</sup> endocrine<sup>25</sup> and cannabinoid receptor pathways,<sup>26</sup> and ibuprofen, a non-steroidal anti-inflammatory drug (NSAID). Understanding the influence on ASD risk of exposure to multiple fever events, and of the timing of these episodes across pregnancy, is also incomplete. Here we report results from a study in a Norwegian birth cohort where questionnaires and capture of cases through a national registry allowed us to investigate associations between prenatal fever and ASD risk. We also examined the potential for antipyretics to modify risk.

## MATERIALS AND METHODS

## Study design and participants

The Norwegian Mother and Child Cohort Study (MoBa)<sup>27</sup> includes 114 500 children born in 1999–2009. ASD cases are identified through the Autism Birth Cohort (ABC) Study,<sup>28</sup> a case–cohort study nested within MoBa. Analyses reflect data collected through December 2014. Children from

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multiple births or with birth weight < 2500 grams or gestational age < 32 weeks (6.6%, Supplementary Figure S1) were excluded. Given questionnaire design, we focused on subjects with gestational ages  $\geq$  32 weeks to ensure that all women could report fever for at least the first 4 weeks of the third trimester. Low birth weight is associated with a multitude of pre- and postnatal risk factors; thus, we also excluded subjects with low birth weight.<sup>29</sup> This exclusion was also motivated by the nearly complete overlap in our study population of preterm and low birth weight status (887 subjects out of 892 with gestational age < 32 weeks had low birth weight, or 99.44%).

Studies were approved by the Regional Committee for Medical and Health Research Ethics for Southeastern Norway and the Columbia University Medical Center Institutional Review Board.

### Case diagnoses

ASD cases were identified through MoBa screening (3, 5 and 7 years), referrals and annual linkages to the Norwegian Patient Register (NPR).<sup>30</sup> Through 2012, potential cases were invited for assessment by research clinicians using standardized diagnostic instruments.<sup>31,32</sup> Best-estimate ASD diagnoses were assigned using *Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition, Text Revision* (DSM-IV-TR)<sup>33</sup> criteria. ASD cases among NPR-identified children not evaluated at the ABC Study Clinic were those assigned *International Classification of Diseases, Tenth Revision* (ICD-10) F84 diagnoses (Supplementary Methods).<sup>34</sup> NPR ASD diagnoses have high validity: 58 out of 60 children with NPR ASD diagnoses met DSM-IV-TR ASD criteria at later ABC clinic assessment (positive predictive value: 96.7%, 95% confidence interval (CI), 87.5–99.4%; false positive rate: 3.3%, 95% CI, 0.6–12.5%).<sup>30</sup>

To explore the possibility that prenatal fever effects may be specific for certain ASD phenotypes, cases were classified as ASD with or ASD without mental retardation/intellectual disability (ID). Comorbidity with ID was based on intelligence quotient (IQ) data from ABC clinic assessments, as available (IQ < 70)<sup>11</sup> or NPR ICD-10 data consistent with a diagnosis of an ID. ASD cases without an ABC clinic IQ score < 70 and who also had not received an NPR ID ICD-10 code were assigned to the ASD without ID group (Supplementary Methods).

### Exposure data

**Exposure timing.** Data on prenatal fever and antipyretic use were obtained from questionnaires completed around gestational weeks 17 and 30, and 6 months postpartum. Mothers reported fever and medication use in 4-week intervals through 13+ and 29+ weeks' gestation, respectively, on the 17- and 30-week questionnaires and from gestational week 30 through parturition on the 6-month postnatal questionnaire (Supplementary Table S1). An interval was considered positive for fever or antipyretic exposure if one or more exposures occurred during that interval. Trimesters were designated by gestational weeks as: first, 0–12 weeks; second, 13–28 weeks; and third, 29 weeks through birth. Overlap in timing across questionnaires was resolved as described in Supplementary Methods. Main analyses included women with at least one completed questionnaire containing prenatal data.

**Fever and antipyretic exposures.** Questionnaire items solicited data from mothers regarding the presence of specific conditions, including fever, along with their timing, as well as the names of medications used for fever, and the timing of that medication use. Response options for presence and timing of fever episodes and medication use varied across the three questionnaires (Supplementary Table S1). To enhance cross-questionnaire comparability, we collapsed data for 17-week questionnaire items—fever with rash and fever > 38.5 °C—into one category. Questionnaire-specific procedures for counting fever episodes and assigning their timing to specific trimesters are detailed further in Supplementary Methods.

We assessed use of any acetaminophen- or ibuprofen-containing medications for the reported indication of fever. Methods for addressing report of multiple medications and timing of medication use are described in Supplementary Methods, along with secondary analysis procedures for examining risk modification by antipyretic use (acetaminophen or the NSAID, ibuprofen).

Supplementary Table S2 summarizes methods for resolving discrepancies in reported fever timing and in the timing of antipyretic use in relationship to fever episodes, along with the number of affected subjects. Inconsistency in reported fever timing took on three major forms. First, some mothers indicated timing of the medication taken for fever and the

name of the antipyretic, but failed to report the specific timing of fever episodes for which they reported taking an antipyretic. In these instances, maternally provided medication timing defined the fever timing. Second, when timing of fever episodes was provided but timing of the selected fever-associated antipyretics (acetaminophen, ibuprofen) was not, maternally provided fever timing defined the timing of medication use. Third, missing fever timings were imputed for the high-exposure subset of mothers who endorsed the 'fever more than three times' item on the 30-week questionnaire but failed to provide complete timing for all reported fever episodes (Supplementary Methods). Supplementary Table S2 shows that the number of affected women, and thus the scope of the problem, was small.

### Potential confounders

We evaluated variables that might influence associations between primary maternal exposures (fever in all three trimesters) and ASD risk: maternal age; smoking and parity; parental education; birth month; and birth year (Supplementary Methods and Supplementary Tables S3A and S3B). Potential confounders demonstrating a significant association ( $P < 0.05$ ) with both the primary exposure (fever in any of the three trimesters) and the outcome (ASD) were retained in our analyses.

### Statistical analysis

**Main analyses.** Crude and adjusted odds ratios (ORs and aORs, respectively) of ASD risk in association with maternal fever in each trimester, and for any time during pregnancy, and their associated 95% CIs were estimated by logistic regression. We first examined associations between fever and risk by fitting separate models for each time period, using all subjects responding to at least one questionnaire containing prenatal data. Analyses examining ASD risk in association with fever at any time during pregnancy included subjects responding to all questionnaires.

Subsequent analyses restricted the study sample to mothers who responded to all questionnaires addressing prenatal fever. We used three adjusted models: (1) Adjusted Model 1 (aOR1), adjusting for fever exposure in either/both of the other trimesters; (2) Adjusted Model 2 (aOR2), adjusting for all other selected confounders; and (3) Adjusted Model 3 (aOR3), adjusting for both fever in other trimesters and all confounders. This same population of respondents was used for stratified analyses comparing ASD risk in association with prenatal fever within the subgroup of ASD cases with comorbid ID and within the ASD subset without such comorbidity.

**Dose–response analyses.** The cumulative effect of maternal fever was estimated by counting numbers of individual time intervals wherein mothers reported fever episodes. We categorized fever exposure into three levels (0 (referent), 1–2,  $\geq$  3 episodes), with exposure periods of any time during pregnancy or > 12 weeks of gestation. Using logistic regression, we estimated ORs and aORs for both exposure periods.

**Fever-associated risk stratified on use of antipyretics.** In exploratory analyses, we examined whether the risk effect of fever exposure was modified by acetaminophen use. Mothers reporting fever in each trimester were divided into two subgroups based on reported use or nonuse of acetaminophen specifically for fever. Crude and adjusted ORs (aOR1, aOR2 and aOR3, as above) of ASD for each subgroup (compared with the no-fever referent) were estimated by logistic regression. We performed similar secondary analyses substituting ibuprofen for acetaminophen to further examine antipyretic modification of fever-associated ASD risk. Although both agents reduce fever, as an NSAID, ibuprofen has anti-inflammatory potential that acetaminophen does not; if, as prior studies have suggested, fever-related activation of maternal immunity mediates neurodevelopmental consequences among offspring, use of ibuprofen as an antipyretic might be anticipated to be associated with greater reduction in fever-associated ASD risk than acetaminophen (Supplementary Methods).

**Supplementary and sensitivity analyses.** Influences of confounders on ORs of ASD were examined individually and sequentially (Supplementary Methods and Supplementary Tables S4A and S4B).

To address possible influences relating to trends across birth years in ASD prevalence (incomplete ascertainment of cases in later birth years, given follow-up in some subjects only through age 5) and maternal fever report, we performed an analysis of fever effects stratified by early (1999–2004) and late (2005–2009) birth year periods.

We also examined fetal sex effects. Trophoblasts from male placentae are reported to respond to infection-related signals with proinflammatory cytokine production,<sup>35,36</sup> consistent with studies suggesting increased risk of preterm birth in males, particularly in the context of infection.<sup>36–38</sup> Because

of low numbers of girls with ASD, we pursued potential influences of sex through sensitivity analyses restricted to boys (Supplementary Methods).

Other sensitivity analyses addressed potential biases relating to gestational age at birth and fever timing imputation. Preterm births

**Table 1.** Characteristics of mothers and children in study population, by fever exposure status and diagnosis

Subject characteristics	All subjects (N = 95 754)	Any fever (N = 15 701)	No fever (N = 80 053)	ASD (N = 583)	Non-case (N = 95 171)	P-value <sup>a</sup>
<i>Parental characteristics</i>						
Maternal age (years), N (%)						< 0.0001
< 20	971 (1.0)	180 (1.1)	791 (1.0)	10 (1.7)	961 (1.0)	
20–24	9691 (10.1)	1605 (10.2)	8086 (10.1)	94 (16.1)	9597 (10.1)	
25–29	31 597 (33.0)	5174 (33.0)	26 423 (33.0)	191 (32.8)	31 406 (33.0)	
30–34	36 893 (38.5)	6090 (38.8)	30 803 (38.5)	188 (32.2)	36 705 (38.6)	
35–39	14 701 (15.4)	2356 (15.0)	12345 (15.4)	91 (15.6)	14 610 (15.4)	
≥ 40	1901 (2.0)	296 (1.9)	1605 (2.0)	9 (1.5)	1892 (2.0)	
Parental education, N (%)						< 0.0001
< 12 years	3261 (3.4)	444 (2.8)	2817 (3.5)	41 (7.0)	3220 (3.4)	
12 years	21 862 (22.8)	3325 (21.2)	18 537 (23.2)	171 (29.3)	21 691 (22.8)	
13–16 years	36 168 (37.8)	5964 (38.0)	30 204 (37.7)	203 (34.8)	35 965 (37.8)	
≥ 17 years	33 033 (34.5)	5737 (36.5)	27 266 (34.1)	160 (27.4)	32 843 (34.5)	
Missing <sup>b</sup>	1460 (1.5)	231 (1.5)	1229 (1.5)	8 (1.4)	1452 (1.5)	
Maternal smoking, N (%)						< 0.0001
Yes	8965 (9.4)	1490 (9.5)	7 475 (9.3)	89 (15.3)	8876 (9.3)	
No	68 929 (72.0)	11 843 (75.4)	57 086 (71.3)	385 (66.0)	68 544 (72.0)	
Missing <sup>b</sup>	17 860 (18.7)	2368 (15.1)	15 492 (19.4)	109 (18.7)	17 751 (18.7)	
Parity, N (%)						< 0.0001
0	42 412 (44.3)	6377 (40.6)	36 035 (45.0)	319 (54.7)	42 093 (44.2)	
≥ 1	53 342 (55.7)	9324 (59.4)	44 018 (55.0)	264 (45.3)	53 078 (55.8)	
Mode of delivery, N (%)						0.065
Spontaneous	77 472 (80.9)	12 604 (80.3)	64 868 (81.0)	450 (77.2)	77 022 (80.9)	
Induced	12 339 (12.9)	2085 (13.3)	10 254 (12.8)	92 (15.8)	12 247 (12.9)	
Cesarean section	5943 (6.2)	1012 (6.4)	4931 (6.2)	41 (7.0)	5902 (6.2)	
<i>Child characteristics</i>						
Sex, N (%)						< 0.0001
Male	49 197 (51.4)	8030 (51.1)	41 167 (51.4)	487 (83.5)	48 710 (51.2)	
Female	46 557 (48.6)	7671 (48.9)	38 886 (48.6)	96 (16.5)	46 461 (48.8)	
Gestational age, N (%)						0.002
32–36 weeks	2552 (2.7)	431 (2.7)	2121 (2.6)	23 (3.9)	2529 (2.7)	
37–38 weeks	15 301 (16.0)	2602 (16.6)	12 699 (15.9)	98 (16.8)	15 203 (16.0)	
39–41 weeks	70 202 (73.3)	11 420 (72.7)	58 782 (73.4)	395 (67.8)	69 807 (73.3)	
≥ 42 weeks	7 699 (8.0)	1248 (7.9)	6451 (8.1)	67 (11.5)	7632 (8.0)	
Birth weight (g), mean (s.d.)						0.009
2500–2999	8 378 (8.7)	1323 (8.4)	7055 (8.8)	68 (11.7)	8310 (8.7)	
3000–3499	28 519 (29.8)	4703 (30.0)	23 816 (29.8)	155 (26.6)	28 364 (29.8)	
3500–3999	36 779 (38.4)	6025 (38.4)	30 754 (38.4)	205 (35.2)	36 574 (38.4)	
4000–4499	17 648 (18.4)	2935 (18.7)	14 713 (18.4)	119 (20.4)	17 529 (18.4)	
≥ 4500	4430 (4.6)	715 (4.6)	3715 (4.6)	36 (6.2)	4394 (4.6)	
Birth year, N (%)						< 0.0001
1999	35 (0.0)	0 (0.0)	35 (0.0)	1 (0.2)	34 (0.0)	
2000	1859 (1.9)	261 (1.7)	1598 (2.0)	17 (2.9)	1842 (1.9)	
2001	3670 (3.8)	597 (3.8)	3073 (3.8)	38 (6.5)	3632 (3.8)	
2002	7713 (8.1)	1159 (7.4)	6554 (8.2)	87 (14.9)	7626 (8.0)	
2003	11 220 (11.7)	1640 (10.4)	9580 (12.0)	110 (18.9)	11 110 (11.7)	
2004	12 091 (12.6)	1992 (12.7)	10 099 (12.6)	83 (14.2)	12 008 (12.6)	
2005	14 024 (14.6)	2373 (15.1)	11 651 (14.6)	86 (14.8)	13 938 (14.6)	
2006	15 707 (16.4)	2509 (16.0)	13 198 (16.5)	60 (10.3)	15 647 (16.4)	
2007	14 387 (15.0)	2654 (16.9)	11 733 (14.7)	53 (9.1)	14 334 (15.1)	
2008	12 001 (12.5)	1958 (12.5)	10 043 (12.5)	41 (7.0)	11 960 (12.6)	
2009	3047 (3.2)	558 (3.6)	2489 (3.1)	7 (1.2)	3040 (3.2)	
Birth month, N (%)						0.156
January	7979 (8.3)	1000 (6.4)	6979 (8.7)	48 (8.2)	7931 (8.3)	
February	7661 (8.0)	1105 (7.0)	6556 (8.2)	51 (8.7)	7610 (8.0)	
March	8610 (9.0)	1446 (9.2)	7164 (8.9)	52 (10.7)	8558 (9.0)	
April	8642 (9.0)	1611 (10.3)	7031 (8.8)	62 (10.6)	8580 (9.0)	
May	8567 (8.9)	1820 (11.6)	6747 (8.4)	47 (8.1)	8520 (9.0)	
June	8024 (8.4)	1750 (11.1)	6274 (7.8)	43 (7.4)	7981 (8.4)	
July	8800 (9.2)	1666 (10.6)	7134 (8.9)	39 (6.7)	8761 (9.2)	
August	8386 (8.8)	1488 (9.5)	6898 (8.6)	37 (6.3)	8349 (8.8)	
September	8037 (8.4)	1211 (7.7)	6826 (8.5)	53 (9.1)	7984 (8.4)	
October	7700 (8.0)	980 (6.2)	6720 (8.4)	55 (9.4)	7645 (8.0)	
November	6763 (7.1)	829 (5.3)	5934 (7.4)	40 (6.9)	6723 (7.1)	
December	6585 (6.9)	795 (5.1)	5790 (7.2)	47 (8.1)	6538 (6.9)	
ASD, N (%)	583 (0.6)	113 (0.7)	470 (0.6)			
Non-case, N (%)	95 171 (99.4)	15 588 (99.3)	79 583 (99.4)			

Abbreviation: ASD, autism spectrum disorder. Key: g, grams. <sup>a</sup>P-values are those associated with  $\chi^2$ -tests comparing prevalence of each characteristic in the ASD and non-case groups. <sup>b</sup>Missing data imputed for subsequent analyses (Supplementary Methods).

(32–36 weeks) might have obscured the ability to assess the impact of fever and antipyretic events in later pregnancy; thus, we restricted to term births (that is, gestational age >36 weeks) in sensitivity analyses. In an additional sensitivity analysis, we excluded mothers who reported high levels of fever exposure on the 30-week questionnaire (>3 fever episodes) without specifying the timing of those episodes (Supplementary Methods).

## RESULTS

### Study cohort

The study sample included 95 754 children (51.4% boys) after exclusions (Supplementary Figure S1). Mean age was 9.4 years (s.d., 2.2 years; range, 5.6–15.2 years) by end of follow-up (31 December, 2014).

Table 1 shows characteristics of mothers and their pregnancies vis-à-vis prenatal fever and offspring diagnosis (ASD, non-case). The mothers of 15 701 children (16.4%) reported fever in one or more 4-week intervals throughout pregnancy. Women reporting fever were more likely to have offspring at earlier gestational ages (<39 weeks), in later cohort birth years (≥2005) and in March through August. Fever exposures were more prevalent, and ASD less prevalent, in more recent birth years (Table 1; Spearman's rank correlation coefficient: both  $P < 0.0001$ ).

### Autism spectrum disorder

We identified 583 cases of ASD (0.6%) through 2014. Males were overrepresented fivefold (Table 1). Mothers of ASD children were younger and less educated than non-case mothers and more likely to smoke and be first-time mothers. ASD offspring identified through end of follow-up were also more often born in earlier cohort years (<2006; higher prevalence of children not yet old enough to be diagnosed).

### Main models

Table 2 shows associations between prenatal fever exposure and ASD risk for any time in pregnancy and by trimester. Women reporting fever at any time during pregnancy had increased odds of ASD in both unadjusted and adjusted models. Examining by trimester, offspring of mothers with second-trimester fever had a 1.4-fold increased risk in adjusted models (aOR, 1.40; 1.11–1.77). The first trimester showed similar, but nonsignificant, point estimates (aOR, 1.34; 0.89–2.02).

The presence of fever in the first trimester was associated with fever episodes in other trimesters. Second-trimester fever was also associated with fever in the third trimester (Pearson's  $\chi^2$ -test: all associations,  $P < 0.0001$ ). To permit analyses that could adjust the fever-associated risk found in one trimester by accounting for fever episodes in other trimesters, we restricted to mothers

completing all questionnaires containing prenatal data. As with results using all questionnaire respondents, offspring of mothers with second-trimester fever had increased risk in the crude model (OR, 1.33; 1.04–1.70; Table 3). Adjustment for fever in other trimesters had little effect. Fever-associated risk in second trimester was similar when adjusting for confounders either alone or in combination with presence of fever in other trimesters (Table 3). The first trimester showed similar but nonsignificant point estimates.

*Fever-associated risk in ASD subsets with and without ID.* As compared with non-cases, ASD cases with comorbid ID showed a tendency toward increased fever-associated risk in fully adjusted models both with exposure in the first (aOR3, 2.28; 0.91–5.75) and the second trimesters (aOR3, 1.64; 0.89–3.03). For ASD cases without ID, fever-associated risk was modestly but significantly increased (1.36-fold) and restricted to second-trimester exposures (Supplementary Table S5).

*Dose–response models.* With exposure at any time during pregnancy, risk increased 1.3-fold with one to two fever episodes (aOR, 1.31; 1.04–1.64) and more than twofold (albeit not significant) with three or more episodes (aOR, 2.15; 0.95–4.84). After gestational week 12, risk increased with higher frequency of exposure (one to two episodes: aOR, 1.30; 1.02–1.66; three or more episodes: aOR, 3.12; 1.28–7.63; Table 4).

*Fever-associated risk stratified on use of antipyretics.* In secondary stratified analyses, we examined whether use of acetaminophen for fever modified fever-associated ASD risk. Risk tended to be lower within each trimester in febrile women who took acetaminophen for fever than in febrile women who did not (compared to the referent group of afebrile women; Supplementary Table S6A). The risk was similar both for women febrile in the second trimester who did and who did not specifically report taking acetaminophen for fever.

Additional secondary stratified analyses examined the potential for modification of fever-associated risk through the use of the NSAID, ibuprofen, given that, unlike acetaminophen, it has anti-inflammatory properties in addition to its antipyretic effects. These analyses were compromised by overall small numbers and cells with zero values. Among febrile women whose offspring were later diagnosed with ASD, none had taken ibuprofen for fever in any trimester (Supplementary Table S6B).

*Supplementary and sensitivity analyses.* Accounting for confounders slightly increased ORs in main models. Birth year, introduced either individually or sequentially into the models, had the most

**Table 2.** Association between maternal fever and risk of ASD in offspring, at any time during pregnancy and by trimester

Exposure period	ASD fever-exposed N (%)	Non-case fever-exposed N (%)	Crude model			Adjusted model				
			OR	95% CI	P-value	aOR <sup>a</sup>	95% CI	P-value		
Any time during pregnancy <sup>b</sup> (N = 79 109)	98 (20.68)	13 509 (17.18)	<b>1.26</b>	<b>1.01</b>	<b>1.57</b>	<b>0.045</b>	<b>1.34</b>	<b>1.07</b>	<b>1.67</b>	<b>0.011</b>
First trimester <sup>c</sup> (N = 95 115)	24 (4.14)	3069 (3.25)	1.29	0.85	1.94	0.229	1.34	0.89	2.02	0.162
Second trimester <sup>d</sup> (N = 87 648)	85 (16.04)	11 067 (12.70)	<b>1.31</b>	<b>1.04</b>	<b>1.66</b>	<b>0.022</b>	<b>1.40</b>	<b>1.11</b>	<b>1.77</b>	<b>0.005</b>
Third trimester <sup>e</sup> (N = 79 748)	17 (3.56)	2627 (3.31)	1.08	0.66	1.75	0.761	1.15	0.70	1.87	0.583

Abbreviations: aOR, adjusted odds ratio; ASD, autism spectrum disorder; CI, confidence interval; OR, odds ratio. Key: bold text represents significant findings,  $P < 0.05$ . <sup>a</sup>Adjusted for: maternal age, smoking and parity; parental education and birth year. <sup>b</sup>Respondents to all three questionnaires containing prenatal fever data: ASD,  $N = 474$ ; non-case,  $N = 78 635$ . <sup>c</sup>All respondents to 17-week prenatal questionnaire: ASD,  $N = 580$ ; non-case,  $N = 94 535$ . <sup>d</sup>All respondents to both the 17- and 30-week prenatal questionnaires: ASD,  $N = 530$ ; non-case,  $N = 87 118$ . <sup>e</sup>All respondents to both the 30-week prenatal and the 6-month postnatal questionnaires: ASD,  $N = 477$ ; non-case,  $N = 79 271$ .

**Table 3.** Association between maternal fever and risk of ASD in offspring, by trimester (respondents to Q1, Q3 and Q4; N = 79 109<sup>a</sup>)

Exposure period	ASD fever-exposed N (%)			Non-case fever-exposed N (%)			Crude model						Adjusted models					
	OR	95% CI	P-value	OR	95% CI	P-value	aOR1 <sup>b</sup>	95% CI	P-value	aOR2 <sup>c</sup>	95% CI	P-value	aOR3 <sup>d</sup>	95% CI	P-value			
First trimester	1.34	0.85	0.209	2 511 (3.19)	1.34	0.207	1.27	0.81	2.00	0.299	1.37	0.87	2.15	0.170	1.29	0.82	2.03	0.272
Second trimester	<b>1.33</b>	<b>1.04</b>	<b>1.70</b>	9 869 (12.55)	<b>1.33</b>	<b>0.023</b>	<b>1.31</b>	<b>1.02</b>	<b>1.68</b>	<b>0.032</b>	<b>1.42</b>	<b>1.11</b>	<b>1.82</b>	<b>0.005</b>	<b>1.40</b>	<b>1.09</b>	<b>1.79</b>	<b>0.008</b>
Third trimester	1.09	0.67	1.76	2 606 (3.31)	1.09	0.741	1.03	0.63	1.68	0.900	1.15	0.71	1.88	0.566	1.08	0.66	1.77	0.746

Abbreviations: aOR, adjusted odds ratio; ASD, autism spectrum disorder; CI, confidence interval; OR, odds ratio. Key: bold text represents significant findings,  $P < 0.05$ . <sup>a</sup>ASD, N = 474; non-case, N = 78 635. <sup>b</sup>aOR1: adjusted for presence of fever in the other trimesters (Adjusted Model 1). <sup>c</sup>aOR2: adjusted for maternal age, smoking and parity; parental education; and birth year (Adjusted Model 2). <sup>d</sup>aOR3: adjusted for presence of fever in the other trimesters and confounder variables (maternal age, smoking and parity; parental education; and birth year) (Adjusted Model 3).

marked influence on ORs in the second trimester compared with other confounders; however, the magnitude of these effects was quite modest (Supplementary Materials; Supplementary Tables S4A and S4B).

We pursued a series of sensitivity analyses to determine whether effects differed in early vs late birth years (1999–2004 vs 2005–2009), as well as for boys, term births (excluding children born at gestational weeks 32–36) or offspring of mothers providing complete, or nearly complete, fever timing on the 30-week questionnaire. In fully adjusted analyses stratified on birth year period, we found that the association of second-trimester fever with increased odds of ASD was only observed in the earlier part of the cohort (1999–2004 births, children aged 10–15 years at end of follow-up: aOR3, 1.86; 1.37–2.52; 2005–2009 births, children aged 5–9 years at end of follow-up: aOR3, 0.88; 0.57–1.37). We also found a first-trimester effect restricted to the later birth year period (2004–2009: aOR3, 1.89; 1.02–3.50; Supplementary Tables S7A and S7B).

For the remaining sensitivity analyses, we found minimal differences in ORs (Supplementary Materials and Supplementary results).

### DISCUSSION

Prenatal fever was associated with increased ASD risk among offspring in the ABC. Effects were strongest in the second trimester but followed similar patterns in the first. Risks were minimally mitigated in women taking acetaminophen for fever in the second trimester. Risks increased markedly and dose dependently with fever frequency, with particularly strong effects after 12 weeks' gestation.

The strengths of our study are its basis in a large, prospective, population-based birth cohort with exposure data collected in 4-week intervals and linkage to a patient registry for case ascertainment. Maternal self-reporting and differences across the three questionnaires may contribute to some exposure misclassification; however, differential reporting is minimized by our study design, as fever reporting precedes the diagnosis of autism. Maternal self-report may also detect fevers that healthcare records might miss. In addition, the overall rate of maternally reported fever in our cohort across pregnancy (16.4%) was similar to that reported in a retrospective study in the US (20.5%) for any fever with infection during pregnancy.<sup>10</sup>

Our findings complement prior literature on prenatal fever and ASD risk.<sup>20,21</sup> Prospective examination of fever exposures through birth revealed that fever-associated risk, most prominent in second trimester, was not influenced by the presence of fever in the other two trimesters. Similar patterns pertained for the first trimester but not the third. The only prior prospective study found an association with prolonged fever in the first and second trimesters but could not exclude a possible third-trimester effect, as no data were collected after 32 weeks' gestation.<sup>20</sup>

To our knowledge, there are no other prospective studies examining maternally reported use of antipyretics for fever and ASD. A retrospective study reporting an association of first- and second-trimester fever with increased ASD risk found that acetaminophen and NSAIDs mitigated fever-associated risks.<sup>21</sup> Data were not separately reported for antipyretics with and without anti-inflammatory potential. Here we found only small risk reduction with use of acetaminophen for fever in conjunction with a small increase in risk among febrile women who did not take acetaminophen. In contrast, none of the women with offspring later diagnosed with ASD used ibuprofen for fever in pregnancy, although these findings must be interpreted with extreme caution, given the low overall frequency of ibuprofen use in this population.

ASD is associated with increased prevalence of autoimmune disorders in mothers and first-degree relatives.<sup>39</sup> Microglial

**Table 4.** Dose–response analysis of the association of maternal fever episodes and risk of ASD in offspring, any time during pregnancy and after 12 weeks of gestation to birth (*N* = 79 109)<sup>a</sup>

Exposure period	Number of fever episodes	ASD N (%)	Non-case N (%)	Crude analysis			Adjusted analysis <sup>b</sup>				
				OR	95% CI	P-value	aOR	95% CI	P-value		
Any time during pregnancy	1–2	92 (19.41)	12 976 (16.50)	1.23	0.98	1.54	0.078	<b>1.31</b>	<b>1.04</b>	<b>1.64</b>	<b>0.023</b>
	≥3	6 (1.27)	533 (0.68)	1.95	0.87	4.39	0.107	2.15	0.95	4.84	0.066
After 12 weeks	1–2	81 (17.09)	11 477 (14.60)	1.22	0.96	1.55	0.111	<b>1.30</b>	<b>1.02</b>	<b>1.66</b>	<b>0.033</b>
	≥3	5 (1.05)	303 (0.39)	<b>2.84</b>	<b>1.17</b>	<b>6.92</b>	<b>0.021</b>	<b>3.12</b>	<b>1.28</b>	<b>7.63</b>	<b>0.013</b>

Abbreviations: aOR, adjusted odds ratio; ASD, autism spectrum disorder; CI, confidence interval; OR, odds ratio. Key: bold text represents significant findings, *P* < 0.05. <sup>a</sup>Study population restricted to mothers responding to all three questionnaires (17-week prenatal, 30-week prenatal and 6-month postnatal); ASD, *N* = 474; non-case, *N* = 78 635. <sup>b</sup>Adjusted for: maternal age, smoking and parity; parental education; birth year.

activation<sup>40–43</sup> and elevated brain chemokine levels<sup>42</sup> are also reported. Animal models of maternal gestational infection or exposure to noninfectious mimics of bacterial (lipopolysaccharide)<sup>44,45</sup> or viral (polyinosinic:polycytidylic acid)<sup>46,47</sup> infection result in neurodevelopmental damage reminiscent of ASD. Evidence from these models suggests that maternal fever-associated immune responses mediate consequences in offspring<sup>47–52</sup> and are abrogated by NSAIDs.<sup>47</sup> As in ASD, effects are most prominent in males.<sup>53</sup> Our results are consistent with these models in that fever is associated with increased risk, risk is accentuated in males and antipyretics tend to decrease fever-associated risk.

Questionnaire analysis did not indicate an association between risk and maternally reported symptoms of infection in individual organ systems that might implicate specific infectious agents. Nonetheless, we are testing the possibility that risk is associated with specific infectious agents through sequence-based and serological assays of samples collected mid-pregnancy and at birth from cases and controls. Linkage to patient register data, including hospitalization records, may also be used in future work to confirm timing and severity of illness episodes. Other evidence relating to severity of illness, such as degree of fever, may also prove informative; however, study questionnaires did not ask mothers to report this information for all time periods in pregnancy.

We acknowledge that our findings are limited by small numbers, particularly for first- and third-trimester exposures to fever and antipyretics; replication in other populations will also be critical before determining the implications of this work for management of fever in pregnancy. However, factors besides small numbers may have contributed to the wider CI we obtained for the first-trimester effect across all birth years, including shorter length of follow-up for ASD outcomes among younger cohort children, heterogeneity in the composition of the ASD group, or both. Our analyses stratified on earlier vs later birth year periods—despite even smaller numbers than in analyses including all birth years—provide evidence within the later birth year group of a more robust first-trimester effect (1.89-fold, with CIs excluding 1). Although the difference between aORs by birth year are not statistically significant in either trimester comparison, precision is lacking for testing such an interaction, and birth-year-dependent differences in the composition of the ASD group (DSM-IV-TR subsets) may have influenced our trimester-based results.

It is also important to bear in mind that causality cannot be definitively established through observational research. Nonetheless, we found consistently increased risk with higher levels of fever exposure. Opposing patterns of prevalence of ASD and fever exposure in our study sample—decreased prevalence of ASD but increased prevalence of fever exposure in later cohort years—may have biased results. However, our age-specific ASD prevalence

patterns are similar to those reported in other work in Norway<sup>54</sup> as well as other Nordic countries, where diagnoses are often registered at ages far exceeding those at which symptoms typically begin.<sup>55</sup> Follow-up studies may resolve whether ASD underascertainment in younger cohort children diminished effect sizes. Birth in later cohort years had a greater influence on ascertainment of higher-functioning cases, as these subsets are typically diagnosed at older ages, as well as more generally for younger members of the cohort, based on reduced length of follow-up. The case sample is thus perhaps weighted toward more severe cases. However, the rate of ID comorbidity did not vary substantially between early and late birth year periods (15.30 vs 13.99%, respectively). Although ID is not a simple proxy for ASD severity, our key finding—an increase in risk for ASD in association with maternal second-trimester fever—was restricted to ASD without ID, suggesting a degree of specificity. Prenatal fever increased risk in the ASD group with ID in the first but not the second trimester, consistent with previous work indicating a relationship of first-trimester fever exposure with severe structural defects of the central nervous and other organ systems.<sup>9</sup> More conclusive analysis awaits detection of additional cases with extended follow-up.

Our findings support the hypothesis that fever and associated immune disturbances are implicated in a subset of ASD cases. Although acetaminophen was associated with a small decrease in risk in the context of fever, prior studies reporting ablation of fever-associated risk with use of a diverse range of medications with antipyretic properties, including NSAIDs as well as acetaminophen—along with our own limited data on ibuprofen—suggest that the choice of antipyretic warrants scrutiny. We have not addressed microbial causes of maternal fever and immune activation. Accordingly, future work should focus on identifying and preventing prenatal infections and inflammatory responses that may contribute to ASD pathogenesis.

#### CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

- 1 Atladottir HO, Thorsen P, Ostergaard L, Schendel DE, Lemcke S, Abdallah M et al. Maternal infection requiring hospitalization during pregnancy and autism spectrum disorders. *J Autism Dev Disord* 2010; **40**: 1423–1430.
- 2 Zerbo O, Qian Y, Yoshida C, Grether JK, Van de Water J, Croen LA. Maternal infection during pregnancy and autism spectrum disorders. *J Autism Dev Disord* 2015; **45**: 4015–4025.
- 3 Lee BK, Magnusson C, Gardner RM, Blomstrom A, Newschaffer CJ, Burstyn I et al. Maternal hospitalization with infection during pregnancy and risk of autism spectrum disorders. *Brain Behav Immun* 2015; **44**: 100–105.
- 4 Fang SY, Wang S, Huang N, Yeh HH, Chen CY. Prenatal infection and autism spectrum disorders in childhood: a population-based case-control study in Taiwan. *Paediatr Perinat Epidemiol* 2015; **29**: 307–316.
- 5 Patterson PH. Maternal infection and immune involvement in autism. *Trends Mol Med* 2011; **17**: 389–394.
- 6 Abdallah MW, Larsen N, Grove J, Norgaard-Pedersen B, Thorsen P, Mortensen EL et al. Amniotic fluid inflammatory cytokines: potential markers of immunologic dysfunction in autism spectrum disorders. *World J Biol Psychiatry* 2013; **14**: 528–538.
- 7 Goines PE, Croen LA, Braunschweig D, Yoshida CK, Grether J, Hansen R et al. Increased midgestational IFN-gamma, IL-4 and IL-5 in women bearing a child with autism: a case-control study. *Mol Autism* 2011; **2**: 13.
- 8 Cordeiro CN, Tsimis M, Burd I. Infections and brain development. *Obstet Gynecol Surv* 2015; **70**: 644–655.
- 9 Dreier JW, Andersen AM, Berg-Beckhoff G. Systematic review and meta-analyses: fever in pregnancy and health impacts in the offspring. *Pediatrics* 2014; **133**: e674–e688.
- 10 Collier SA, Rasmussen SA, Feldkamp ML, Honein MA, National Birth Defects Prevention S. Prevalence of self-reported infection during pregnancy among control mothers in the National Birth Defects Prevention Study. *Birth Defects Res A Clin Mol Teratol* 2009; **85**: 193–201.
- 11 Dombrowski SC, Martin RP, Huttunen MO. Association between maternal fever and psychological/behavior outcomes: a hypothesis. *Birth Defects Res A Clin Mol Teratol* 2003; **67**: 905–910.
- 12 Sidman RL, Rakic P. Neuronal migration, with special reference to developing human brain: a review. *Brain Res* 1973; **62**: 1–35.
- 13 Iruretagoyena JI, Davis W, Bird C, Olsen J, Radue R, Teo Broman A et al. Differential changes in gene expression in human brain during late first trimester and early second trimester of pregnancy. *Prenat Diagn* 2014; **34**: 431–437.
- 14 Rezaie P, Male D. Colonisation of the developing human brain and spinal cord by microglia: a review. *Microsc Res Tech* 1999; **45**: 359–382.
- 15 Schumann CM, Bloss CS, Barnes CC, Wideman GM, Carper RA, Akshoomoff N et al. Longitudinal magnetic resonance imaging study of cortical development through early childhood in autism. *J Neurosci* 2010; **30**: 4419–4427.
- 16 Bauman ML, Kemper TL. Neuroanatomic observations of the brain in autism: a review and future directions. *Int J Dev Neurosci* 2005; **23**: 183–187.
- 17 Amaral DG, Schumann CM, Nordahl CW. Neuroanatomy of autism. *Trends Neurosci* 2008; **31**: 137–145.
- 18 Chen JA, Penagarikano O, Belgard TG, Swarup V, Geschwind DH. The emerging picture of autism spectrum disorder: genetics and pathology. *Annu Rev Pathol* 2015; **10**: 111–144.
- 19 Reiner O, Karzbrun E, Kshirsagar A, Kaibuchi K. Regulation of neuronal migration, an emerging topic in autism spectrum disorders. *J Neurochem* 2016; **136**: 440–456.
- 20 Atladottir HO, Henriksen TB, Schendel DE, Parner ET. Autism after infection, febrile episodes, and antibiotic use during pregnancy: an exploratory study. *Pediatrics* 2012; **130**: e1447–e1454.
- 21 Zerbo O, Iosif AM, Walker C, Ozonoff S, Hansen RL, Hertz-Picciotto I. Is maternal influenza or fever during pregnancy associated with autism or developmental delays? Results from the CHARGE (Childhood Autism Risks from Genetics and Environment) study. *J Autism Dev Disord* 2013; **43**: 25–33.
- 22 Liew Z, Ritz B, Virk J, Olsen J. Maternal use of acetaminophen during pregnancy and risk of autism spectrum disorders in childhood: a Danish national birth cohort study. *Autism Res* 2016; **9**: 951–958.
- 23 Werler MM, Mitchell AA, Hernandez-Diaz S, Honein MA. Use of over-the-counter medications during pregnancy. *Am J Obstet Gynecol* 2005; **193**: 771–777.
- 24 Du K, Ramachandran A, Jaeschke H. Oxidative stress during acetaminophen hepatotoxicity: sources, pathophysiological role and therapeutic potential. *Redox Biol* 2016; **10**: 148–156.
- 25 Holm JB, Chalmei C, Modick H, Jensen LS, Dierkes G, Weiss T et al. Aniline is rapidly converted into paracetamol impairing male reproductive development. *Toxicol Sci* 2016; **150**: 178–179.
- 26 Ghanem CI, Perez MJ, Manautou JE, Mottino AD. Acetaminophen from liver to brain: new insights into drug pharmacological action and toxicity. *Pharmacol Res* 2016; **109**: 119–131.
- 27 Magnus P, Irgens LM, Haug K, Nystad W, Skjaerven R, Stoltenberg C et al. Cohort profile: the Norwegian Mother and Child Cohort Study (MoBa). *Int J Epidemiol* 2006; **35**: 1146–1150.
- 28 Stoltenberg C, Schjølberg S, Bresnahan M, Hornig M, Hirtz D, Dahl C et al. The Autism Birth Cohort: a paradigm for gene-environment-timing research. *Mol Psychiatry* 2010; **15**: 676–680.
- 29 Kramer MS. Determinants of low birth weight: methodological assessment and meta-analysis. *Bull World Health Organ* 1987; **65**: 663–737.
- 30 Bresnahan M, Hornig M, Schultz AF, Gunnes N, Hirtz D, Lie KK et al. Association of maternal report of infant and toddler gastrointestinal symptoms with autism: evidence from a prospective birth cohort. *JAMA Psychiatry* 2015; **72**: 466–474.
- 31 Lord C, Rutter M, Le Couteur A. Autism Diagnostic Interview-Revised: a revised version of a diagnostic interview for caregivers of individuals with possible pervasive developmental disorders. *J Autism Dev Disord* 1994; **24**: 659–685.
- 32 Lord C, Risi S, Lambrecht L, Cook EH Jr, Leventhal BL, DiLavore PC et al. The autism diagnostic observation schedule-generic: a standard measure of social and communication deficits associated with the spectrum of autism. *J Autism Dev Disord* 2000; **30**: 205–223.
- 33 APA. *Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition, Text Revision (DSM-IV-TR)*. American Psychiatric Association: Arlington, 2000.
- 34 World Health Organization. *Mental Disorders: A Glossary and Guide to Their Classification in Accordance With the 10th Revision of the International Classification of Diseases: Research Diagnostic Criteria (ICD-10)*. World Health Organization: Geneva, Switzerland, 1993.
- 35 Yeganeh M, Watson CS, Martins A, Kim SO, Reid G, Challis JR et al. Effect of Lactobacillus rhamnosus GR-1 supernatant and fetal sex on lipopolysaccharide-induced cytokine and prostaglandin-regulating enzymes in human placental trophoblast cells: implications for treatment of bacterial vaginosis and prevention of preterm labor. *Am J Obstet Gynecol* 2009; **200**: e1–e8.
- 36 Challis J, Newnham J, Petraglia F, Yeganeh M, Bocking A. Fetal sex and preterm birth. *Placenta* 2013; **34**: 95–99.
- 37 Brettell R, Yeh PS, Impey LW. Examination of the association between male gender and preterm delivery. *Eur J Obstet Gynecol Reprod Biol* 2008; **141**: 123–126.
- 38 McGregor JA, Leff M, Orleans M, Baron A. Fetal gender differences in preterm birth: findings in a North American cohort. *Am J Perinatol* 1992; **9**: 43–48.
- 39 McDougle CJ, Landino SM, Vahabzadeh A, O'Rourke J, Zurcher NR, Finger BC et al. Toward an immune-mediated subtype of autism spectrum disorder. *Brain Res* 2015; **1617**: 72–92.
- 40 Morgan JT, Chana G, Pardo CA, Achim C, Semendeferi K, Buckwalter J et al. Microglial activation and increased microglial density observed in the dorsolateral prefrontal cortex in autism. *Biol Psychiatry* 2010; **68**: 368–376.
- 41 Tetreault NA, Hakeem AY, Jiang S, Williams BA, Allman E, Wold BJ et al. Microglia in the cerebral cortex in autism. *J Autism Dev Disord* 2012; **42**: 2569–2584.
- 42 Vargas DL, Nascimbene C, Krishnan C, Zimmerman AW, Pardo CA. Neuroglial activation and neuroinflammation in the brain of patients with autism. *Ann Neurol* 2005; **57**: 67–81.
- 43 Edmonson C, Ziats MN, Rennert OM. Altered glial marker expression in autistic post-mortem prefrontal cortex and cerebellum. *Mol Autism* 2014; **5**: 3.
- 44 Kirsten TB, Lippi LL, Bevilacqua E, Bernardi MM. LPS exposure increases maternal corticosterone levels, causes placental injury and increases IL-1β levels in adult rat offspring: relevance to autism. *PLoS One* 2013; **8**: e82244.
- 45 Foley KA, MacFabe DF, Kavaliers M, Ossenkopp KP. Sexually dimorphic effects of prenatal exposure to lipopolysaccharide, and prenatal and postnatal exposure to propionic acid, on acoustic startle response and prepulse inhibition in adolescent rats: Relevance to autism spectrum disorders. *Behav Brain Res* 2015; **278**: 244–256.
- 46 Malkova NV, Yu CZ, Hsiao EY, Moore MJ, Patterson PH. Maternal immune activation yields offspring displaying mouse versions of the three core symptoms of autism. *Brain Behav Immun* 2012; **26**: 607–616.
- 47 De Miranda J, Yaddanapudi K, Hornig M, Villar G, Serge R, Lipkin WI. Induction of Toll-like receptor 3-mediated immunity during gestation inhibits cortical neurogenesis and causes behavioral disturbances. *MBio* 2010; **1**: e00176–10.
- 48 Bauman MD, Iosif AM, Smith SE, Bregere C, Amaral DG, Patterson PH. Activation of the maternal immune system during pregnancy alters behavioral development of rhesus monkey offspring. *Biol Psychiatry* 2014; **75**: 332–341.
- 49 Choi GB, Yim YS, Wong H, Kim S, Kim H, Kim SV et al. The maternal interleukin-17a pathway in mice promotes autism-like phenotypes in offspring. *Science* 2016; **351**: 933–939.
- 50 Hsiao EY. Immune dysregulation in autism spectrum disorder. *Int Rev Neurobiol* 2013; **113**: 269–302.
- 51 Hsiao EY, McBride SW, Chow J, Mazmanian SK, Patterson PH. Modeling an autism risk factor in mice leads to permanent immune dysregulation. *Proc Natl Acad Sci USA* 2012; **109**: 12776–12781.
- 52 Garay PA, Hsiao EY, Patterson PH, McAllister AK. Maternal immune activation causes age- and region-specific changes in brain cytokines in offspring throughout development. *Brain Behav Immun* 2013; **31**: 54–68.

- 53 Xuan IC, Hampson DR. Gender-dependent effects of maternal immune activation on the behavior of mouse offspring. *PLoS One* 2014; **9**: e104433.
- 54 Suren P, Bakken IJ, Aase H, Chin R, Gunnes N, Lie KK *et al*. Autism spectrum disorder, ADHD, epilepsy, and cerebral palsy in Norwegian children. *Pediatrics* 2012; **130**: e152–e158.
- 55 Atladottir HO, Gyllenberg D, Langridge A, Sandin S, Hansen SN, Leonard H *et al*. The increasing prevalence of reported diagnoses of childhood psychiatric disorders: a descriptive multinational comparison. *Eur Child Adolesc Psychiatry* 2015; **24**: 173–183.



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