

EUR Research Information Portal

Meta-analysis of epigenome-wide association studies in newborns and children show widespread sex differences in blood DNA methylation

Published in:

Mutation Research - Reviews in Mutation Research

Publication status and date:

Published: 01/01/2022

DOI (link to publisher):

[10.1016/j.mrrev.2022.108415](https://doi.org/10.1016/j.mrrev.2022.108415)

Document Version

Publisher's PDF, also known as Version of record

Document License/Available under:

CC BY-NC-ND

Citation for the published version (APA):

Solomon, O., Huen, K., Yousefi, P., Küpers, L. K., González, J. R., Suderman, M., Reese, S. E., Page, C. M., Gruzieva, O., Rzehak, P., Gao, L., Bakulski, K. M., Novoloaca, A., Allard, C., Pappa, I., Llambrich, M., Vives, M., Jima, D. D., Kvist, T., ... Holland, N. (2022). Meta-analysis of epigenome-wide association studies in newborns and children show widespread sex differences in blood DNA methylation. *Mutation Research - Reviews in Mutation Research*, 789, Article 108415. <https://doi.org/10.1016/j.mrrev.2022.108415>

[Link to publication on the EUR Research Information Portal](#)

Terms and Conditions of Use

Except as permitted by the applicable copyright law, you may not reproduce or make this material available to any third party without the prior written permission from the copyright holder(s). Copyright law allows the following uses of this material without prior permission:

- you may download, save and print a copy of this material for your personal use only;
- you may share the EUR portal link to this material.

In case the material is published with an open access license (e.g. a Creative Commons (CC) license), other uses may be allowed. Please check the terms and conditions of the specific license.

Take-down policy

If you believe that this material infringes your copyright and/or any other intellectual property rights, you may request its removal by contacting us at the following email address: openaccess.library@eur.nl. Please provide us with all the relevant information, including the reasons why you believe any of your rights have been infringed. In case of a legitimate complaint, we will make the material inaccessible and/or remove it from the website.

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Mutation Research-Reviews in Mutation Research

journal homepage: www.elsevier.com/locate/mutrev

Review



Meta-analysis of epigenome-wide association studies in newborns and children show widespread sex differences in blood DNA methylation

Olivia Solomon^{a,1}, Karen Huen^{a,*}, Paul Yousefi^{b,c}, Leanne K. Küpers^d, Juan R. González^{e,f,g}, Matthew Suderman^c, Sarah E. Reese^h, Christian M. Page^{i,j}, Olena Gruzieva^{k,l}, Peter Rzehak^m, Lu Gaoⁿ, Kelly M. Bakulski^o, Alexei Novoloaca^p, Catherine Allard^q, Irene Pappa^{r,s}, Maria Llambrich^{e,f,g}, Marta Vives^{e,f,g,t}, Dereje D. Jima^{u,v}, Tuomas Kvist^w, Andrea Baccarelli^x, Cory White^y, Faisal I. Rezwan^{z,aa}, Gemma C. Sharp^c, Gwen Tindula^a, Anna Bergström^{k,l}, Veit Grote^m, John F. Dou^o, Elena Isaevska^{ab}, Maria C. Magnusⁱ, Eva Corpeleijn^d, Patrice Perron^{q,ac}, Vincent W.V. Jaddoe^{s,ad}, Ellen A. Nohr^{ae,af}, Lea Maitre^{e,f,g}, Maria Foraster^{e,f,g,ag}, Cathrine Hoyo^{u,ah}, Siri E. Håbergⁱ, Jari Lahti^w, Dawn L. DeMeo^{ai}, Hongmei Zhang^{aj}, Wilfried Karmaus^{aj}, Inger Kull^{ak,al}, Berthold Koletzko^m, Jason I. Feinberg^{am}, Luigi Gagliardi^{an}, Luigi Bouchard^{ao,ap}, Cecilia Høst Ramlau-Hansen^{aq}, Henning Tiemeier^{r,ar}, Gillian Santorelli^{as}, Rachel L. Maguire^{ah,at}, Darina Czamara^{au}, Augusto A. Litonjua^{av}, Jean-Paul Langhendries^{aw}, Michelle Plusquin^{ax}, Johanna Lepeule^{ay}, Elisabeth B. Binder^{au,az}, Elvira Verduci^{ba,bb}, Terence Dwyer^{bc,bd,be}, Ángel Carracedo^{bf,bg}, Natalia Ferre^{bh}, Brenda Eskenazi^{bi}, Manolis Kogevinas^{e,f,g,bj}, Tim S. Nawrot^{ax,bk}, Monica C. Munthe-Kaas^{i,bl}, Zdenko Herceg^p, Caroline Relton^c, Erik Melén^{ak,al}, Dariusz Gruszfeld^{bm}, Carrie Bretonⁿ, M.D. Fallin^{am}, Akram Ghantous^p, Wenche Nystad^{bn}, Barbara Heude^{bo}, Harold Snieder^d, Marie-France Hivert^{ac,bp,bq}, Janine F. Felix^{s,ad}, Thorkild I.A. Sørensen^{b,c,br,bs}, Mariona Bustamante^{e,f,g}, Susan K. Murphy^{at}, Katri Raikkönen^w, Emily Oken^{bp}, John W. Holloway^{aa,bt}, Syed Hasan Arshad^{bt,bu}, Stephanie J. Londonⁿ, Nina Holland^a

^a Children's Environmental Health Laboratory, Division of Environmental Health Sciences, School of Public Health, University of California, Berkeley, CA, USA

^b Population Health Sciences, Bristol Medical School, University of Bristol, Bristol, UK

^c MRC Integrative Epidemiology Unit, Population Health Sciences, Bristol Medical School, University of Bristol, BS8 2BN, UK

^d University of Groningen, University Medical Center Groningen, Department of Epidemiology, Groningen, The Netherlands

^e ISGlobal, Barcelona Institute for Global Health, Dr Aiguader 88, 08003 Barcelona, Spain

^f Universitat Pompeu Fabra (UPF), Barcelona, Spain

^g CIBER Epidemiología y Salud Pública (CIBERESP), Madrid, Spain

^h Epidemiology Branch, National Institute of Environmental Health Sciences, National Institutes of Health, Department of Health and Human Services, Research Triangle Park, NC, USA

ⁱ Centre for Fertility and Health, Norwegian Institute of Public Health, Oslo, Norway

^j Oslo Centre for Biostatistics and Epidemiology, Oslo University Hospital, Oslo, Norway

^k Institute of Environmental Medicine, Karolinska Institutet, Stockholm, Sweden

^l Center for Occupational and Environmental Medicine, Region Stockholm, Sweden

^m Div. Metabolic and Nutritional Medicine, Dept. Pediatrics, Dr. von Hauner Children's Hospital, Ludwig-Maximilians Universität München (LMU), Munich, Germany

ⁿ Department of Preventive Medicine, University of Southern California, Los Angeles, CA 90089, USA

^o School of Public Health, University of Michigan, Ann Arbor, MI 48109, USA

^p International Agency for Research on Cancer, Lyon, France

^q Centre de Recherche du Centre Hospitalier Universitaire de Sherbrooke, QC, Canada

^r Department of Child and Adolescent Psychiatry/ Psychology, Erasmus Medical Center, Sophia Children's Hospital, P.O. Box 2060, 3000 CB Rotterdam, The Netherlands

Abbreviations: EWAS, Epigenome Wide Association Studies; IQR, interquartile range; lncRNAs, long intergenic noncoding RNAs; PACE, Pregnancy And Childhood Epigenetics Consortium.

* Correspondence to: School of Public Health, UC Berkeley, 2121 Berkeley Way, CA 94720, USA.

E-mail address: khuen@berkeley.edu (K. Huen).

<https://doi.org/10.1016/j.mrrev.2022.108415>

Received 20 April 2021; Received in revised form 27 February 2022; Accepted 8 March 2022

Available online 14 March 2022

1383-5742/© 2022 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

- ^s The Generation R Study Group, Erasmus MC, University Medical Center Rotterdam, P.O. Box 2060, 3000 CB Rotterdam, The Netherlands
- ^t Centre for Genomic Regulation (CRG), The Barcelona Institute of Science and Technology, Dr. Aiguader 88, Barcelona 08003, Spain
- ^u Center for Human Health and the Environment, North Carolina State University, Raleigh, NC 27606, USA
- ^v Bioinformatics Research Center, North Carolina State University, Raleigh, NC 27606, USA
- ^w Department of Psychology and Logopedics, Faculty of Medicine, University of Helsinki, Finland
- ^x Laboratory of Precision Environmental Biosciences, Columbia University Mailman School of Public Health, New York, NY, USA
- ^y Merck Exploratory Science Center, Merck Research Laboratories, Cambridge, MA 02141, USA
- ^z Department of Computer Science, Aberystwyth University, Aberystwyth, Ceredigion, SY23 3DB, United Kingdom
- ^{aa} Human Development and Health, Faculty of Medicine, University of Southampton, Southampton General Hospital, Southampton, UK
- ^{ab} Cancer Epidemiology Unit, Department of Medical Sciences, University of Turin, Turin, Italy
- ^{ac} Department of Medicine, Universite de Sherbrooke, QC, Canada
- ^{ad} Department of Pediatrics, Erasmus MC, University Medical Center Rotterdam, P.O. Box 2060, 3000 CB Rotterdam, The Netherlands
- ^{ae} Institute of Clinical Research, University of Southern Denmark, Odense, Denmark
- ^{af} Centre of Women's, Family and Child Health, University of South-Eastern Norway, Kongsberg, Norway
- ^{ag} PHAGEX Research Group, Blanquerna School of Health Science, Universitat Ramon Llull, Barcelona, Spain
- ^{ah} Department of Biological Sciences, North Carolina State University, NC, USA
- ^{ai} Channing Division of Network Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA
- ^{aj} Division of Epidemiology, Biostatistics and Environmental Health, School of Public Health, University of Memphis, Memphis, USA
- ^{ak} Department of Clinical Science and Education, Södersjukhuset, Karolinska Institutet, Stockholm, Sweden
- ^{al} Sachs' Children and Youth Hospital, Södersjukhuset, Stockholm, Sweden
- ^{am} Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD 21205, USA
- ^{an} Department of Woman and Child Health, Ospedale Versilia, Azienda USL Toscana Nord Ovest, Viareggio, Italy
- ^{ao} Department of Biochemistry and Functional Genomics, Université de Sherbrooke, QC, Canada
- ^{ap} Department of Medical Biology, CIUSSS Saguenay-Lac-Saint-Jean, Chicoutimi Hospital, Saguenay, QC, Canada
- ^{aq} Department of Public Health, Research Unit for Epidemiology, Aarhus University, 8000 Aarhus C, Denmark
- ^{ar} Department of Social and Behavioral Science, Harvard TH Chan School of Public Health, 677 Huntington Ave, Boston, MA, USA
- ^{as} Bradford Institute of Health Research, Bradford Royal Infirmary, Bradford BD9 6RJ, UK
- ^{at} Department of Obstetrics and Gynecology, Duke University Medical Center, Durham, NC 27701, USA
- ^{au} Dept. Translational Research in Psychiatry, Max-Planck-Institute of Psychiatry, Munich, Germany
- ^{av} Division of Pediatric Pulmonology, Department of Pediatrics, University of Rochester Medical Center, Rochester, NY, USA
- ^{aw} CHC, St Vincent, Liège-Rocourt, Belgium
- ^{ax} Centre for Environmental Sciences, Hasselt University, Hasselt, Belgium
- ^{ay} Univ. Grenoble Alpes, Inserm, CNRS, Team of Environmental Epidemiology Applied to Reproduction and Respiratory Health, IAB, 38000 Grenoble, France
- ^{az} Department of Psychiatry and Behavioral Sciences, Emory University School of Medicine, USA
- ^{ba} Department of Pediatrics, Ospedale dei Bambini Vittore Buzzi, University of Milan, Milan, Italy
- ^{bb} Department of Health Sciences, University of Milan, Milan, Italy
- ^{bc} Clinical Sciences, Heart Group, Murdoch Children's Research Institute, Melbourne, Australia
- ^{bd} Department of Pediatrics, University of Melbourne, Melbourne, Australia
- ^{be} Nuffield Department of Women's & Reproductive Health, University of Oxford, Oxford, UK
- ^{bf} Grupo de Medicina Xenómica, Fundación Pública Galega de Medicina Xenómica, Instituto de Investigación Sanitaria de Santiago de Compostela (IDIS), SERGAS, Santiago de Compostela, Spain
- ^{bg} Centro de Investigación en Red de Enfermedades Raras (CIBERER) y Centro Nacional de Genotipado (CEGEN-PRB3), Universidad de Santiago de Compostela, Santiago de Compostela, Spain
- ^{bh} Pediatric Nutrition and Human Development Research Unit, Universitat Rovira i Virgili, IISPV, Reus, Spain
- ^{bi} Center for Environmental Research and Children's Health, School of Public Health, University of California, Berkeley, CA, USA
- ^{bj} IMIM (Hospital del Mar Medical Research Institute), Carrer del Dr. Aiguader 88, 08003 Barcelona, Spain
- ^{bk} Department Public Health & Primary care, Leuven University, Belgium
- ^{bl} Department of Pediatric Oncology and Hematology, Oslo University Hospital, Norway
- ^{bm} Neonatal Department, Children's Memorial Health Institute, Warsaw, Poland
- ^{bn} Department of Chronic Diseases and Ageing, Division of Mental and Physical Health, Norwegian Institute of Public Health, Oslo, Norway
- ^{bo} Université de Paris, Centre for Research in Epidemiology and Statistics (CRESS), INSERM, INRAE, F-75004 Paris, France
- ^{bp} Department of Population Medicine, Harvard Medical School, Harvard Pilgrim Health Care Institute, Boston, MA, USA
- ^{bq} Diabetes Unit, Massachusetts General Hospital, Boston, MA, USA
- ^{br} Department of Public Health, Section of Epidemiology, University of Copenhagen, Copenhagen, Denmark
- ^{bs} The Novo Nordisk Foundation Center for Basic Metabolic Research, Section on Metabolic Genetics, Faculty of Medical and Health Sciences, University of Copenhagen, Copenhagen, Denmark
- ^{bt} Clinical and Experimental Sciences, Faculty of Medicine, University of Southampton, Southampton, UK
- ^{bu} David Hide Asthma and Allergy Research Centre, Isle of Wight, UK

ARTICLE INFO

Keywords:
DNA methylation
Sex
Children
Cord blood
EWAS

ABSTRACT

Background: Among children, sex-specific differences in disease prevalence, age of onset, and susceptibility have been observed in health conditions including asthma, immune response, metabolic health, some pediatric and adult cancers, and psychiatric disorders. Epigenetic modifications such as DNA methylation may play a role in the sexual differences observed in diseases and other physiological traits.

Methods: We performed a meta-analysis of the association of sex and cord blood DNA methylation at over 450,000 CpG sites in 8438 newborns from 17 cohorts participating in the Pregnancy And Childhood Epigenetics (PACE) Consortium. We also examined associations of child sex with DNA methylation in older children ages 5.5–10 years from 8 cohorts (n = 4268).

Results: In newborn blood, sex was associated at Bonferroni level significance with differences in DNA methylation at 46,979 autosomal CpG sites ($p < 1.3 \times 10^{-7}$) after adjusting for white blood cell proportions and batch. Most of those sites had lower methylation levels in males than in females. Of the differentially methylated CpG

¹ These authors contributed equally to the work.

sites identified in newborn blood, 68% (31,727) met look-up level significance ($p < 1.1 \times 10^{-6}$) in older children and had methylation differences in the same direction.

Conclusions: This is a large-scale meta-analysis examining sex differences in DNA methylation in newborns and older children. Expanding upon previous studies, we replicated previous findings and identified additional autosomal sites with sex-specific differences in DNA methylation. Differentially methylated sites were enriched in genes involved in cancer, psychiatric disorders, and cardiovascular phenotypes.

1. Introduction

There is a growing body of literature demonstrating that the *in utero* environment can impact health later in life [1–5]. DNA methylation is a commonly studied epigenetic mark that can influence gene expression without change in DNA sequence and is one mechanism through which early-life exposures might contribute to the developmental origins of disease [6]. Exposures to chemicals during pregnancy such as those found in tobacco smoke and air pollution, as well as perinatal characteristics such as birth weight and gestational age, have been associated with differences in umbilical cord blood DNA methylation [7–11]. Furthermore, site-specific differential methylation of cord blood DNA has also been associated with later-life health outcomes including asthma and insulin sensitivity [12–14].

In addition to exposures and health outcomes, inter-individual differences in DNA methylation levels are also impacted by sex. Among females, DNA methylation plays an important role in X-chromosome inactivation [15]. Prior studies have shown sex to be associated with DNA methylation measured in blood at birth (umbilical cord blood), [16–20] in older children [19,21,22], and in adults [21,23–26] as well as in placenta [20,27,28]. As expected, there are widespread differences in DNA methylation levels between sexes at X chromosome CpG sites; however, these studies also reported significant differences in methylation of autosomes [18,21]. Furthermore, autosomal sites differentially methylated between sexes were enriched in genes involved in pathways related to RNA splicing, DNA repair, the nervous system and behavior [18,21]. Most prior studies have been limited in sample size, with fewer than 200 subjects. It is likely that a much larger meta-analysis would improve power to identify CpG sites with smaller DNA methylation differences between males and females at birth, a critical developmental period. Significant sex differences in disease prevalence, age of onset, and susceptibility across the life course have been observed for various conditions such as asthma and allergies, immune response, metabolic health, some pediatric and adult cancers, and psychiatric disorders [29–35]. Therefore, identifying the differences in DNA methylation between males and females may highlight the genes that play an active role in the biological mechanisms involved in sex-dependent differences impacting health.

We performed a meta-analysis of associations between sex and DNA methylation in newborn blood samples and conducted a follow-up meta-analysis in blood from older children in multiple cohorts. We also investigated enrichment of sex-associated differential methylation in specific biological pathways and diseases.

2. Material and methods

2.1. Participating cohorts

PACE consists of over 40 international birth and child cohorts with a goal of performing coordinated Epigenome Wide Association Studies (EWAS) followed by meta-analysis to understand relationships between methylation and both exposures and child health outcomes [36]. Twenty-one independent cohorts contributed data to this study. We included 8438 newborns from 17 cohorts in the analysis of newborn blood DNA methylation and sex (ALSPAC, CHAMACOS, CHS, EARLI, EXPOmICS, GECKO, Gen3G, Generation R, GOYA, INMA, IOW F2, MoBa1, MoBa2, MoBa3, NEST,PREDO, Viva). For the child methylation

analysis, we included 4268 children from eight cohorts (ALSPAC, BAMSE, CHAMACOS, CHOP, Generation R, HELIX, IOW F1, Viva). Detailed methods on the individual cohorts participating in the cord blood and child analyses are provided in the [supplementary methods](#). All cohorts obtained written informed consent from participants prior to data collection which was approved by local ethics committees.

2.2. Methylation measurement and quality control

DNA methylation was measured using the Illumina Infinium HumanMethylation450 BeadChip [37] in all but one study (child blood samples from the IOWF1 cohort) that used the Illumina Infinium Methylation EPIC BeadChip. DNA from newborn or child blood samples underwent bisulfite conversion using the EZ-96 DNA Methylation kit (Zymo Research Corporation, Irvine, USA). Methylation quality control and normalization was conducted at the cohort level, as described in the [supplementary material](#). β -values representing proportion of methylation at each CpG site (ranging from 0 = completely unmethylated to 1 = completely methylated) were used as the methylation outcome. In order to minimize the influence of outlier methylation values, β -values more extreme than 3 times the interquartile range below the 25th percentile or above the 75th percentile were removed prior to all cohort analyses.

2.3. Sex descriptive

As part of quality control, each cohort checked for sex-mismatches using the *getSex* function in the R package *minfi* [38] and sex mismatches were removed prior to individual cohort analyses. The number of participants for each cohort excludes sex mismatches.

2.4. Cohort specific statistical analyses

Each cohort performed independent EWAS according to a common analysis plan. Each cohort used recorded child sex with females as the reference group. Each study used batch covariates most appropriate for their cohort (e.g. principal components or plate number) or a method such as ComBat [39]. Cell composition was estimated using estimate-CellCounts in the *minfi* R package [38]. For cord blood analyses, the ‘CordBlood’ reference data set [40] was used to estimate proportions of seven cell types (CD8 + T-cells, CD4 + T-cells, NK cells, B-cells, monocytes, granulocytes, and nucleated red blood cells), while older child models used the ‘Blood’ reference data set [41] which estimates proportions of six cell types (CD8 + T-cells, CD4 + T-cells, NK cells, B-cells, monocytes, and granulocytes). Cohorts were also given the option to adjust for genetic ancestry in their models, and this information is included in cohort specific methods.

Models were run using M-type multiple robust linear regression [*rlm* () in the *MASS* R package] [42] to control for potential heteroscedasticity and influential outliers in the methylation data. In the primary cord blood analysis, the exposure was sex with the outcome of newborn methylation β -values, adjusting for seven estimated cell counts and batch covariates. In the primary older child models, the exposure was sex with the outcome of child methylation β -values, adjusting for six estimated cell counts, age of the child at blood draw, and batch covariates.

2.5. Meta-analysis

All cohorts submitted the results of their cohort level EWAS to the Children's Environmental Health Laboratory (N. Holland-PI) at the University of California, Berkeley, USA. We then performed a fixed effects meta-analysis weighted by the inverse of the variance—using the software METAL [43]—for the main model, which adjusted for seven cell-type proportions and batch. Shadow meta-analyses were conducted independently by L. Küpers at the University of Bristol, UK to verify results. All further analyses were conducted in R version 3.5.2 [44]. Since all but one study utilized the 450 K BeadChip array (child blood samples from the IOWF1 cohort use the EPIC BeadChip) only probes present on the 450 K BeadChip array were included in the analysis. We excluded SNP control probes ($n = 65$). The majority of cohorts included probes mapping to the X and Y chromosomes; however, some cohorts were only able to provide results for autosomal probes leaving a total sample size of $N = 8438$ for autosomes, and $N = 5213$ for subjects with data for sex chromosomes. Filtering of previously identified cross-reactive probes [45] was performed during processing of meta-analysis results. For autosomal probes, this left a total of 390,810 CpG sites measured for association with sex at birth in the meta-analysis.

We adjusted for multiple hypothesis testing using the stringent Bonferroni method, and considered CpG sites with Bonferroni adjusted p -values < 0.05 significant (e.g. 1.3×10^{-7} for 390,810 tests for autosomes in newborns and 1.1×10^{-6} for 46,979 tests for lookup level correction in children). Summary statistics from the genome-wide DNA methylation meta-analysis are available at figshare (10.6084/m9.figshare.14228927).

To distinguish the relative contribution of these two explanations, we used one cohort (GOYA) as a reference in which to identify a group of CpGs with no true biological signal ($P > 0.2$) and recalculated λ values for this subset of CpGs in the other cohorts.

2.6. Enrichment analyses

Before enrichment analysis was performed, CpG sites were annotated to nearby genes using the *IlluminaHumanMethylation450kanno.ilmn12.hg19* package. We defined $I^2 > 50\%$ as reflective of a high level of between-study heterogeneity [46] and restricted enrichment analysis to those CpGs with $I^2 \leq 50\%$, which included 17,243 CpGs (in 8059 genes) for the cord blood analysis and 10,436 CpGs (in 5572 genes) for the older child analysis.

Using these genes, we performed enrichment analyses at two different levels: pathways and diseases. Detection of KEGG pathway database [47] over-representation against a universal *Homo Sapien* background was assessed by hypergeometric tests [48] using the *gometh()* function in the package *missMethyl* [49]. This function, which was designed specifically for gene set enrichment analysis of methylation data, minimizes bias due to the uneven distribution of probes in the Illumina 450 K and EPIC BeadChip arrays. Hypergeometric over-representation was also performed against the *DisGeNET* [50] curated repository of gene-disease associations using the *enrichDGN()* function in the *DOSE* package [51]. A Bonferroni corrected cutoff of 0.05 was used for significance of pathways and diseases (e.g. 1.52×10^{-4} for 322 tests for pathways and 4.16×10^{-6} for 3779 tests for diseases).

3. Results

3.1. Newborns

Results from 17 independent cohorts from the Pregnancy And Childhood Epigenetics (PACE) Consortium were included in the newborn meta-analysis ($N = 8438$). Newborn cohort sizes ranged from 53 to 1319 participants. There was an even distribution of males (51%) and females (49%). Two cohorts, NEST and EARLI, performed separate models for European and non-European participants, resulting in two

additional datasets ($N = 19$ datasets total). The majority of datasets were made up of participants of European ancestry ($N = 15$ datasets, $N = 7576$ participants). Other datasets included Hispanic, Mexican-American, African-American, and mixed ethnicities. A summary of the participating newborn cohorts and datasets is included in Table 1.

The results of the individual cohort level newborn models are summarized in Supplemental Table 1. As expected, nearly all CpG sites ($N = 9618$, 99.8%) on the X chromosome were significantly differentially methylated between males and females. The average effect size (absolute value) expressed as a methylation beta value for differentially methylated CpG sites on the X chromosome was 0.18 (equals 18% methylation). In autosomes, there were a total of 46,979 Bonferroni significant sex-associated CpG sites out of a total of 390,810 autosomal CpG sites. The lambda (λ) value, a measure of p -value inflation, for the meta-analysis in autosomes only was 4.87. For cohort specific analyses, λ ranged from 1.18 to 2.67 with a sample-size weighted average of 1.91 for autosome only data. All Bonferroni significant CpGs for autosomes are presented in Supplemental Table 2.

The plot in Fig. 1a shows sites in autosomes with lower methylation in males below the null line and sites with higher methylation in males above the null line. Differentially methylated CpGs were observed across all autosomes. The majority (67%) of sex-associated sites on autosomes had lower methylation in males than females (Fig. 2). The CpG-specific differences in methylation levels between males and females were generally small with a median (interquartile range, IQR) difference in methylation of 0.62% (0.61%) for positive differences and 0.88% (1.1%) for negative differences (Fig. 2a).

Among the top Bonferroni significant sites with effect sizes greater than 0.05 (absolute value) listed in Supplemental Table 2, *cg26921482*, which annotated to *TBC1D24*, had the largest effect size with mean methylation 23% lower in newborn males than females. Two CpGs also annotated to *ZNF696* and had higher methylation in females than males. Additionally, some of the most differentially methylated CpGs annotated to lincRNA genes (*LINC01347* and *LINC00346*) and a protein coding gene, *PPP1R3G*.

As expected, CpGs differentially methylated in relation to sex annotated to genes that were enriched for several biological processes and diseases. The top 15 KEGG pathways are summarized in Fig. 3a with

Table 1

Characteristics of cohorts included in the meta-analysis of differences by sex in cord blood DNA methylation.

	N	N-boy	N-girl	Ethnicity
ALSPAC	894	438	456	European
CHAMACOS	363	181	182	Mexican-American
GHS	248	101	147	Hispanic and non-Hispanic white
EARLI (1) ^a	82	45	37	European
EARLI (2) ^a	53	25	28	Non-European
EXPOsoMICS ^b	388	207	181	European
GECKO	252	135	117	European
Gen3G	176	81	95	European
Generation R	1319	675	644	European
GOYA	518	260	258	European
INMA	385	197	188	European
IOW F2	124	64	60	European
MoBa1	1051	560	491	European
MoBa2	671	336	335	European
MoBa3	249	124	125	European
NEST (1) ^a	198	100	98	African American
NEST (2) ^a	170	84	86	European
PREDO	812	429	383	European
Viva	485	254	231	European
Meta-analysis	8438	4296 (51%)	4142 (49%)	

^a EARLI and NEST cohorts ran separate epigenome wide association studies for each ethnic population.

^b EXPOsoMICS is composed of three cohorts: Rhea, Environage, and Piccolipi.

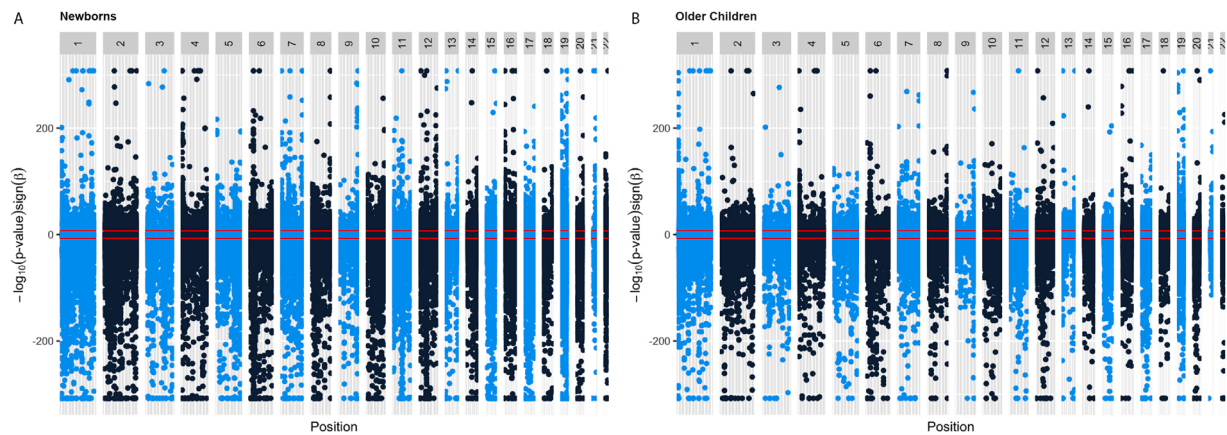


Fig. 1. Plot of meta-analysis EWAS results of differential methylation by sex in (a) newborns and (b) children. Sites with higher methylation in males compared to females are plotted above the x-axis while those with lower methylation in males compared to females are shown below the x-axis. The red lines represent the Bonferroni thresholds for significant CpG sites in each direction (higher and lower methylation in males compared to females) The gray boxes indicate the chromosome and the plot colors vary between blue and black for visual clarity between different chromosomes. The varying widths of the chromosomes corresponds to the length of the chromosomes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

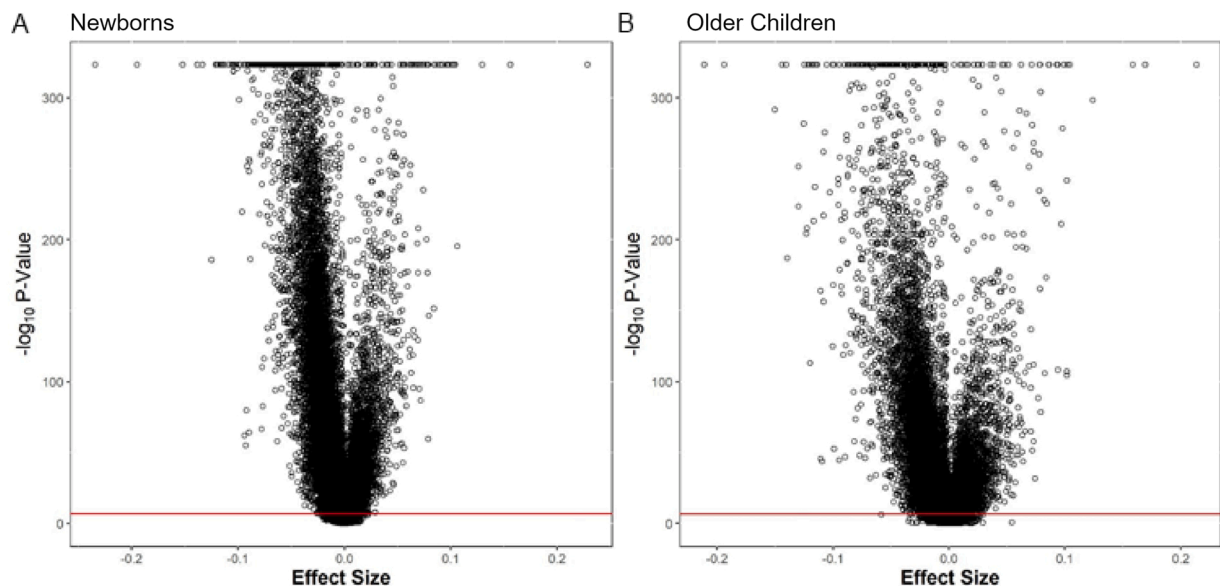


Fig. 2. Volcano plots of meta-analysis EWAS results of differential methylation by sex in (a) newborns and (b) children. Absolute effect sizes ranged from 0 to 0.23 (methylation β -value). Overall, there were more CpG sites with lower methylation in males compared to females.

results sorted from most to least significant, and size of circles representing the number of genes included in that pathway. KEGG pathways fell into groups containing cancer, signaling, endocrine, addiction, and longevity. Only four enriched pathways of 322 tested were Bonferroni significant, including several signaling pathways. Disease enrichment analyses showed 83 significant diseases of the 3779 tested. Genes to which significant CpG sites were annotated were significantly enriched in mental disorders as well as cancer-related outcomes (e.g. ductal carcinoma, neuroendocrine tumors, and thyroid neoplasms) and cardiovascular phenotypes (e.g. systemic arterial pressure, congenital heart defects, blood pressure) (Fig. 4a).

3.2. Children

For the analysis in older children, data from nine independent cohorts were meta-analyzed ($N = 4268$) (Table 2). Child cohorts ranged from 234 to 1053 participants with an average of 497 participants per cohort and had a similar distribution of males (53%) and females (47%).

Similar to the newborn participants, the majority of child datasets contained participants of European ancestry ($N = 4034$ from 7 cohorts), with other contributions from a Mexican-American cohort. Lambdas for individual autosomal analyses ranged from 1.05 to 5.59 (Supplemental Table 3).

Among older children, most of the X chromosome sites (9313) were significant. For the autosomes, there were 40,219 Bonferroni significant sites associated with child sex (Supplemental Table 4). Like newborns, the majority of significant autosomal CpG sites had lower methylation levels in males than in females, which can be seen on the plot in Fig. 1b. The effect size of differential methylation was small and similar to that in newborns with a median (IQR) difference in methylation of 0.62% (0.67%) among sites with significant positive differences and 0.94% (1.0%) among sites with significant negative differences (Fig. 2b).

Among the top Bonferroni significant sites with effect sizes greater than 0.05 (absolute value), the CpG with the largest effect size (21% lower methylation in males than females) was cg12691488, which annotated to a lincRNA gene (*LINC01347*). Two significantly associated

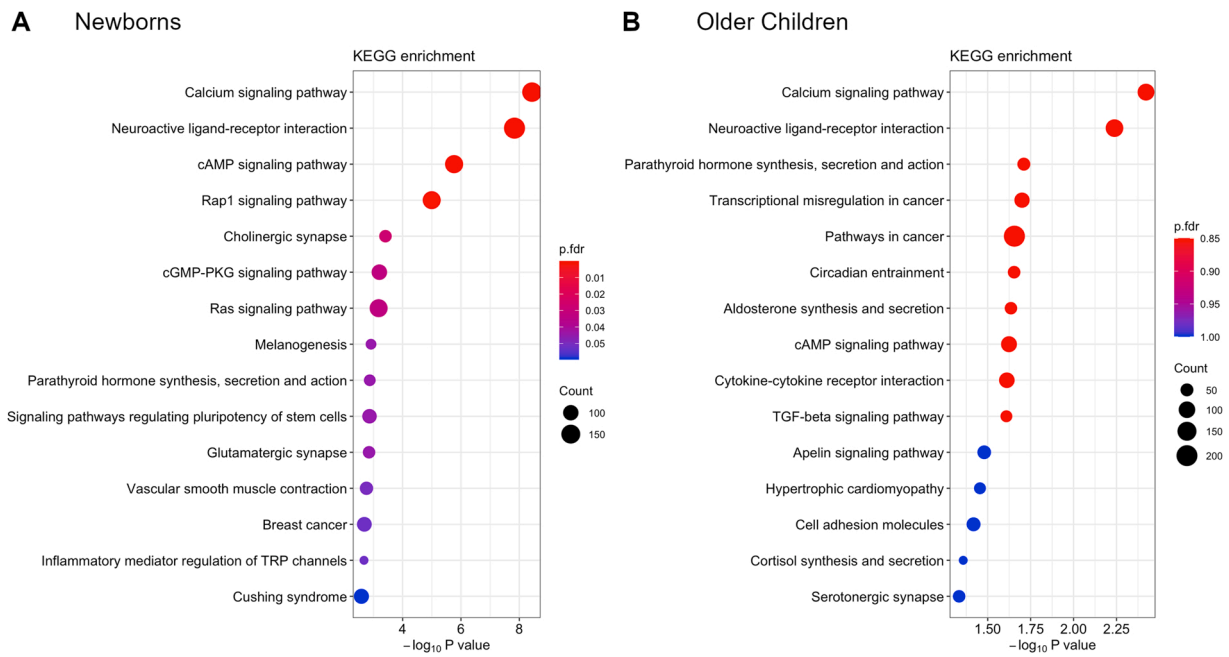


Fig. 3. Kyoto Encyclopedia of Genes and Genomes (KEGG) pathways with enrichment differences between males and females in (a) newborn and (b) older children. The size of the circles represents the number of differentially methylated genes in a pathway.

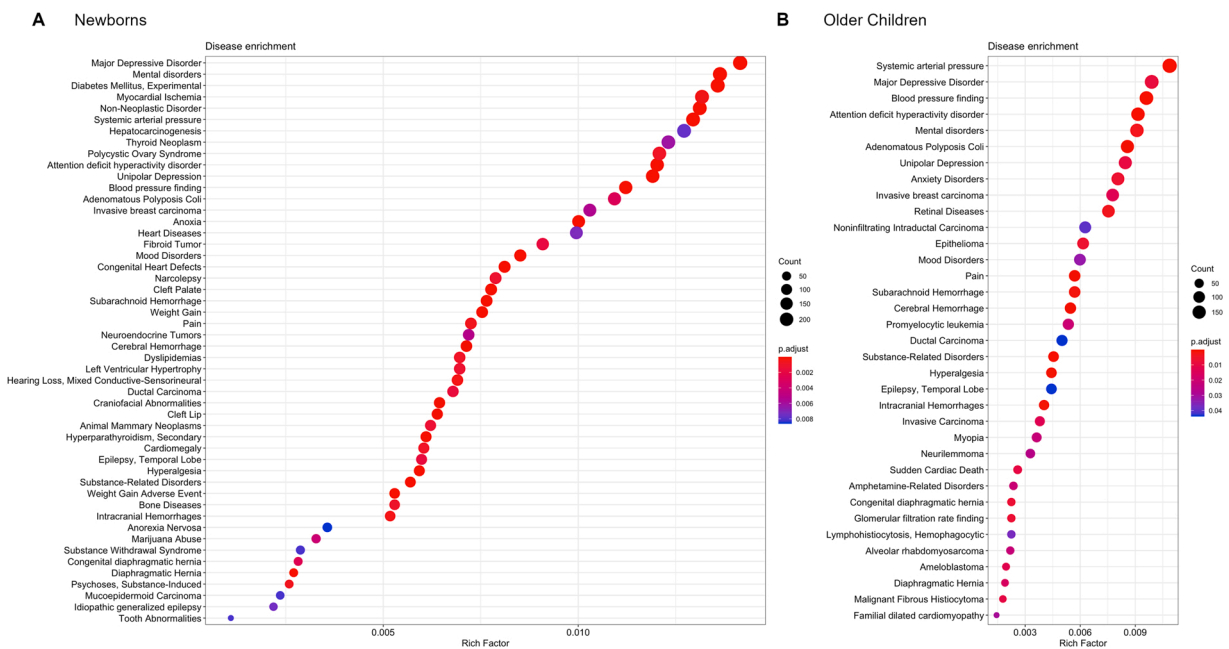


Fig. 4. Diseases with significant enrichment differences between males and females in (a) newborns and (b) older children. Disease enrichment analysis was performed using *DisGeNET*. The size of the circles represent the number of differentially methylated genes in a pathway.

CpGs with lower methylation in males than females mapped to *FRG1BP* and three significantly associated CpGs with higher methylation in males than females mapped to *ZNF696*. Several significant CpGs mapped to *PPP1R3G* and had higher methylation in males compared to females.

The top 15 enriched KEGG pathways are summarized in Fig. 3b with results sorted from lowest to highest p-value, and size of circles representing the number of genes included in that pathway. Of the 322 KEGG pathways tested, none were statistically significant after adjusting for multiple testing (Fig. 3b). The top KEGG pathways predominantly belonged to groups associated with signaling, neuronal and endocrine functions. Of the 3779 diseases tested, 35 had Bonferroni-corrected

enrichment p-values lower than 0.05. Implicated genes are involved in blood pressure, hemorrhage, carcinomas, and mental disorders (Fig. 4b).

3.3. Comparison of newborns and older children

There was considerable overlap between significant sites in newborns and children. Of the 46,979 CpG significant in newborns, 68% (31,850) met look-up level significance ($p < 1.1 \times 10^{-6}$ for 46,979 tests) in the smaller dataset of older children (Supplemental Table 5) demonstrating that many of these relationships with sex persisted over

Table 2

Characteristics of cohorts included in the meta-analysis of differences by sex in child blood DNA methylation.

	Mean Age (Yr)	N	N-boy	N-girl	Ethnicity
ALSPAC	7.5	959	479	480	European
BAMSE	8.3	450	250	200	European
CHAMACOS	9.1	234	109	125	Mexican-American
CHOP	5.5	360	172	188	European
Generation R	6.0	464	227	237	European
HELIX	8.0	1053	581	472	European
IOW F1	10.0	289	186	103	European
Viva	7.9	459	241	218	European
Total		4268	2245	2023	
			(53%)	(47%)	

time. Of these overlapping sites, 99.6% (31,727) show methylation differences in the same direction. Additionally, there were 10,229 CpGs that were Bonferroni-significant (genome-wide significance, $p < 1.1 \times 10^{-7}$) only in the older children, despite the smaller size of this dataset (Supplemental Table 6).

4. Discussion

This large-scale epigenome-wide meta-analysis involving multiple cohorts demonstrates widespread differences in methylation of autosomes between males and females at birth measured in newborn blood and most of these differences persist into later childhood. We report over 45,000 of the nearly 400,000 tested CpG sites to be significantly differentially methylated with small but consistently observed differences between males and females at birth and over 40,000 significant differences in older children with similar effect sizes. As expected, in both newborns and children, these differences were enriched in genes involved in a range of biological pathways important for development, but there was also sex-specific enrichment in cancer pathways and genes implicated in psychiatric disorders and cardiovascular phenotypes.

We compared our findings to prior studies investigating cord or peripheral blood methylation differences by sex (Supplemental Table 7). Only one prior meta-analysis by McCarthy et al. [21] has looked specifically at differential methylation between males and females, and this was assessed using the Illumina 27 K chip. Although a few cohorts contributed cord-blood data, most of the cohorts included in their analysis used adult blood data. This study reported 187 significant autosomal CpGs, of which, in our newborn meta-analysis, we replicate 167 (90%) at genome-wide significance and same direction of effect and in our child meta-analysis, 164 (89%) at genome-wide significance and same direction of effect. Another study by Yousefi et al. [18] reported 3031 CpGs with sex differences in cord-blood for a subset of the CHAMACOS population (which also contributed data to this meta-analysis). Our newborn meta-analysis replicated 2762 (91%) of the Yousefi et al. significant CpGs with the same direction of effect, and our child meta-analysis replicated 2709 (89%) significant CpGs in the same direction of effect. The newborn meta-analysis adds 44,107 autosomal CpGs not previously identified in studies focused on methylation differences by sex with increased sample size and after adjustment of cord blood cell-type heterogeneity. We also report 37,397 new autosomal CpG sites differentially methylated by sex in the blood of older children. Although we identified a large number of differentially methylated CpG sites, it should be noted that for many of these sites, the effect sizes were quite small.

Interestingly, in both newborns and older children, about two-thirds of the significantly differentially methylated sites had lower methylation in males than females. In general, greater gene expression is observed with lower methylation when CpG sites are in the promoter region. Hypermethylation in females is expected in X chromosome CpG sites due

to X chromosome inactivation in females; however, we found that differences in methylation by sex are not limited to sex-chromosomes and that the higher methylation pattern for females is also common outside of sex-chromosomes. Notably, the opposite trend has been observed in placenta, where the majority of differentially methylated sites in autosomes had higher methylation in males than females [27]. Our finding indicates that there are many autosomal CpG sites that are differentially methylated between males and females; however, most conventional EWAS adjust for sex allowing for these differences to be accounted for in sex-independent analyses.

The CpG with the largest negative association with newborn sex (lower methylation in males compared to females) annotated to *TBC1D24*, and was also significantly associated with sex in older children. *TBC1D24* encodes for a protein involved in neuronal development and has also been associated with epilepsy and neurological disorders [52,53]; sex differences have been observed for both conditions [54,55]. The CpG with the largest positive association with child sex (lower methylation in females than males) was *LINC01347*, and was also significantly associated with newborn sex. Another significantly associated CpG site in both newborns and children also annotated to a lincRNA, *LINC00346*. Long intergenic noncoding RNAs (lincRNAs) affect gene expression through regulation of chromatin [56]. Differences in their expression levels have been associated with neuropsychiatric disorders (e.g. schizophrenia), cancers, and coronary artery disease [57–59]. Furthermore, differences in lincRNA expression profiles by sex have previously been observed [59,60].

Sex-specific differences have been observed in numerous diseases and studies show evidence for an epigenetic role in sexual dimorphism for disease [61]. Diseases with observed differences by sex include asthma [62], autoimmune and allergic diseases [32,63], cardiovascular diseases [64], and pediatric infectious diseases [31]. Early-life differences between males and females also suggests an underlying developmental component, especially in newborns who have had fewer lifetime exposures [65]. We report many biological pathways and diseases where the genes to which differentially methylated sites annotate are enriched in both newborns and children. While some differences are expected since the progression of development in females and males is naturally different, other differences may be related to disease risk. Some of the most significant disease pathways have been previously shown to differ between sexes. Our disease enrichment analysis included several psychiatric disorders, and studies have shown that anxiety disorders are more common and more severe in women [66]. In concordance with our findings, another recent study of differential methylation by sex in cord blood also reported significant enrichment of genes related to neurodevelopmental disorders [67]. Autism is diagnosed in males more often than females, and there are differences in the features of autism in each sex [68]. In children, genes involved in ADHD were significantly enriched for differentially methylated CpG sites. ADHD diagnoses are two-fold higher in males than females with different behaviors associated with the sexes [69]. A prior study in the CHAMACOS cohort also reported methylation differences between males and females in genes involved in neurological disorders [18]. Our data suggest that DNA methylation may represent one mechanism contributing to the developmental differences between males and females that impact sex-dependent differences in health.

We also observed inflated λ values in this meta-analysis, particularly for cohorts with larger sample sizes. λ , also referred to as the genomic inflation factor, is a measure of p-value inflation where a value > 1 implies some inflation of the observed test statistics. Such inflation could be due to the presence of residual confounding or to abundance of true biological signal, which is possible given the phenotype of interest and large number of associations identified even in autosomes. To distinguish the relative contribution of these two explanations (residual confounding or abundance of true biological signal), we used one cohort (GOYA) as a reference in which to identify a group of CpGs with no true biological signal ($P > 0.2$) and recalculated λ values for this subset of

CpGs in the other cohorts. For all cohorts, newly calculated lambdas were closer to one but still somewhat inflated (Supplemental Tables 8 and 9) suggesting that abundance of true signal does contribute to but cannot entirely explain the inflated λ values observed.

Our study has several limitations and strengths. Although our study included cohorts of multiple ancestries, including European, Hispanic, and African American, most participants were of European ancestry. More work involving a larger number of non-European descent participants is needed to ensure generalizability of results. Individual cohorts used different normalization methods for methylation data; however, prior studies within the PACE consortium show little difference in final EWAS results from differently normalized data, so we do not expect this to strongly impact the final meta-analysis results [7]. Since this study did not assess if the methylation changes are impacting gene expression, we cannot confirm if these methylation differences extend to functional changes. These results warrant follow-up to assess if these methylation changes do indeed impact gene expression in order to confirm the biological significance of these findings [2,70,71]. Although the *gometh()* function takes into account the bias introduced by the uneven distribution of probes in the 450 K and EPIC BeadChip arrays in our pathway analyses, the hypergeometric over-representation analysis for disease enrichment (enrichDGN) does not. Further, our analyses were restricted to cord and peripheral blood. Sex-specific methylation in other tissues, such as placenta, may also have implications for disease across the life course.

We report novel findings of autosomal methylation differences between males and females using robust statistical models with a large sample size that was well-powered to assess small effect sizes. We used a cord blood reference dataset, which includes nucleated red blood cells to estimate and adjust for cell-type heterogeneity in newborns [72]. All cohorts ensured correct classification of sex prior to analyses using sex chromosome methylation data as a quality control measure. We also included analyses of methylation at two distinct time-points (newborns and older children) suggesting that methylation differences by sex at many of these CpG sites were relatively stable throughout childhood.

In summary, we observed numerous autosomal methylation differences in blood between males and females, which is likely to be important for normal sex-specific biological development. However, differentially methylated CpG sites were enriched in genes involved in diseases and pathways with differential prevalence between sexes. These findings may suggest that early life DNA methylation differences represent a potential mechanism contributing to regulation of differential disease prevalence by sex.

Funding

For all studies, funding information can be found in the [Supplementary Material \(Supplementary Methods\)](#).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

For all studies, acknowledgments can be found in the [Supplementary Material \(Supplementary Methods\)](#).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.mrrev.2022.108415](https://doi.org/10.1016/j.mrrev.2022.108415).

References

- [1] T. Roseboom, S. de Rooij, R. Painter, The dutch famine and its long-term consequences for adult health, *Early Hum. Dev.* 82 (2006) 485–491.
- [2] D.J. Barker, In utero programming of chronic disease, *Clin. Sci.* 95 (1998) 115–128.
- [3] S.A. Leonard, K.M. Rasmussen, J.C. King, B. Abrams, Trajectories of maternal weight from before pregnancy through postpartum and associations with childhood obesity, *Am. J. Clin. Nutr.* 106 (2017) 1295–1301.
- [4] G.H. Kim, K. Berger, S. Rauch, K. Kogut, C.H. Birgit, M.C. Antonia, K. Huen, B. Eskenazi, N. Holland, Association of prenatal urinary phthalate metabolite concentrations and childhood BMI and obesity, *Pediatr. Res.* 82 (2017) 405.
- [5] N. Slopen, E.B. Loucks, A.A. Appleton, I. Kawachi, L.D. Kubzansky, A.L. Non, S. Buka, S.E. Gilman, Early origins of inflammation: an examination of prenatal and childhood social adversity in a prospective cohort study, *Psychoneuroendocrinology* 51 (2015) 403–413.
- [6] T. Bianco-Miotto, J.M. Craig, Y.P. Gasser, S.J. van Dijk, S.E. Ozanne, Epigenetics and DOHaD: from basics to birth and beyond, *J. Dev. Orig. Health Dis.* 8 (2017) 513–519.
- [7] B.R. Joubert, J.F. Felix, P. Yousefi, K.M. Bakulski, A.C. Just, C. Breton, S.E. Reese, C.A. Markunas, R.C. Richmond, C. Xu, L.K. Küpers, S.S. Oh, C. Hoyo, O. Gruzieva, C. Söderhäll, L.A. Salas, N. Baiz, H. Zhang, J. Lepeule, C. Ruiz, S. Ligthart, T. Wang, J.A. Taylor, L. Duijts, G.C. Sharp, S.A. Jankipersadsing, R.M. Nilsen, A. Vaez, M. D. Fallin, D. Hu, A.A. Litonjua, B.F. Fuemmeler, K. Huen, J. Kere, I. Kull, M. Munthe-Kaas, U. Gehring, M. Bustamante, M. Saurel-Coubizolles, B.M. Quraishi, J. Ren, J. Tost, J.R. Gonzalez, M.J. Peters, S.E. Häberg, Z. Xu, J.B. van Meurs, T. R. Gaunt, M. Kerkhof, E. Corpeleijn, A.P. Feinberg, C. Eng, A.A. Baccarelli, S. E. Benjamin Neelon, A. Bradman, S.K. Merid, A. Bergström, Z. Herceg, H. Hernandez-Vargas, B. Brunekreef, M. Pinart, B. Heude, S. Ewart, J. Yao, N. Lemonnier, O.H. Franco, M.C. Wu, A. Hofman, W. McArdle, dv. Van, F. Falahi, M.W. Gillman, L.F. Barcellos, A. Kumar, M. Wickman, S. Guerra, M. Charles, J. Holloway, C. Auffray, H.W. Tiemeier, G.D. Smith, D. Postma, M. Hivert, B. Eskenazi, M. Vrijheid, H. Arshad, J.M. Antó, A. Dehghan, W. Karmaus, I. Annesi-Maesano, J. Sunyer, A. Ghantous, G. Pershagen, N. Holland, S.K. Murphy, D. L. DeMeo, E.G. Burchard, C. Ladd-Acosta, H. Snieder, W. Nystad, G.H. Koppelman, C.L. Relton, V.W.V. Jaddoe, A. Wilcox, E. Melén, S.J. London, DNA methylation in newborns and maternal smoking in pregnancy: genome-wide consortium meta-analysis, *Am. J. Hum. Genet.* 98 (2016) 680–696.
- [8] O. Gruzieva, C.J. Xu, C.V. Breton, I. Annesi-Maesano, J.M. Antó, C. Auffray, S. Ballereau, T. Bellander, J. Bousquet, M. Bustamante, M.A. Charles, Y. de Kluizenaar, H.T. den Dekker, L. Duijts, J.F. Felix, U. Gehring, M. Guxens, V. V. Jaddoe, S.A. Jankipersadsing, S.K. Merid, J. Kere, A. Kumar, N. Lemonnier, J. Lepeule, W. Nystad, C.M. Page, S. Panasevich, D. Postma, R. Slama, J. Sunyer, C. Söderhäll, J. Yao, S.J. London, G. Pershagen, G.H. Koppelman, E. Melén, Epigenome-wide meta-analysis of methylation in children related to prenatal NO2 air pollution exposure, *Environ. Health Perspect.* 125 (2017) 104–110.
- [9] O. Gruzieva, C.J. Xu, P. Yousefi, C. Relton, S.K. Merid, C.V. Breton, L. Gao, H. E. Volk, J.I. Feinberg, C. Ladd-Acosta, K. Bakulski, C. Auffray, N. Lemonnier, M. Plusquin, A. Ghantous, Z. Herceg, T.S. Nawrot, C. Pizzi, L. Richiardi, F. Rusconi, P. Vineis, M. Kogevinas, J.F. Felix, L. Duijts, H.T. den Dekker, V.W.V. Jaddoe, J. L. Ruiz, M. Bustamante, J.M. Antó, J. Sunyer, M. Vrijheid, K.B. Gutzkow, R. Grazuleviciene, C. Hernandez-Ferrer, I. Annesi-Maesano, J. Lepeule, J. Bousquet, A. Bergström, I. Kull, C. Söderhäll, J. Kere, U. Gehring, B. Brunekreef, A.C. Just, R.J. Wright, C. Peng, D.R. Gold, I. Kloog, D.L. DeMeo, G. Pershagen, G. H. Koppelman, S.J. London, A.A. Baccarelli, E. Melén, Prenatal particulate air pollution and DNA methylation in newborns: an epigenome-wide meta-analysis, *Environ. Health Perspect.* 127 (2019) 57012.
- [10] S.K. Merid, A. Novoloaca, G.C. Sharp, L.K. Küpers, A.T. Kho, R. Roy, L. Gao, I. Annesi-Maesano, P. Jain, M. Plusquin, M. Kogevinas, C. Allard, F.O. Vehmeijer, N. Kazmi, L.A. Salas, F.I. Rezwan, H. Zhang, S. Sebent, D. Czamara, S.L. Rifas-Shiman, P.E. Melton, D.A. Lawlor, G. Pershagen, C.V. Breton, K. Huen, N. Baiz, L. Gagliardi, T.S. Nawrot, E. Corpeleijn, P. Perron, L. Duijts, E.A. Nohr, M. Bustamante, S.L. Ewart, W. Karmaus, S. Zhao, C.M. Page, Z. Herceg, M. R. Jarvelin, J. Lahti, A.A. Baccarelli, D. Anderson, P. Kachroo, C.L. Relton, A. Bergström, B. Eskenazi, M.H. Soomro, P. Vineis, H. Snieder, L. Bouchard, V. W. Jaddoe, T.I.A. Sørensen, M. Vrijheid, S.H. Arshad, J.W. Holloway, S.E. Häberg, P. Magnus, T. Dwyer, E.B. Binder, D.L. DeMeo, J.M. Vonk, J. Newnham, K. G. Tantisira, I. Kull, J.L. Wiemels, B. Heude, J. Sunyer, W. Nystad, M.C. Munthe-Kaas, K. Räikkönen, E. Oken, R.C. Huang, S.T. Weiss, J.M. Antó, J. Bousquet, A. Kumar, C. Söderhäll, C. Almqvist, A. Cardenas, O. Gruzieva, C.J. Xu, S.E. Reese, J. Kere, P. Brodin, O. Solomon, M. Wielscher, N. Holland, A. Ghantous, M.F. Hivert, J.F. Felix, G.H. Koppelman, S.J. London, E. Melén, Epigenome-wide meta-analysis of blood DNA methylation in newborns and children identifies numerous loci related to gestational age, *Genome Med.* 12 (2020) 25–29.
- [11] L.K. Küpers, C. Monneraue, G.C. Sharp, P. Yousefi, L.A. Salas, A. Ghantous, C. M. Page, S.E. Reese, A.J. Wilcox, D. Czamara, A.P. Starling, A. Novoloaca, S. Lent, R. Roy, C. Hoyo, C.V. Breton, C. Allard, A.C. Just, K.M. Bakulski, J.W. Holloway, T. M. Everson, C. Xu, R. Huang, D. van der Plaats, A. Wielscher, S.K. Merid, V. Ullemar, F.I. Rezwan, J. Lahti, J. van Dongen, S.A.S. Langie, T.G. Richardson, M.C. Magnus, E.A. Nohr, Z. Xu, L. Duijts, S. Zhao, W. Zhang, M. Plusquin, D.L. DeMeo, O. Solomon, J.H. Heimovaara, D.D. Jima, L. Gao, M. Bustamante, P. Perron, R. O. Wright, I. Hertz-Picciotto, H. Zhang, M.R. Karagas, U. Gehring, C.J. Marsit, L. J. Beilin, J.M. Vonk, M. Jarvelin, A. Bergström, A.K. Örtqvist, S. Ewart, P.M. Villa, S.E. Moore, G. Willemsen, A.R.L. Perron, S.E. Häberg, T.I.A. Sørensen, J.A. Taylor, K. Räikkönen, I.V. Yang, K. Nohr, T.S. Nawrot, M.J. Silver, Y.Y. Gong, L. Richiardi, M. Kogevinas, A.A. Litonjua, B. Eskenazi, K. Huen, H. Mbarek, R.L. Maguire,

- T. Dwyer, M. Vrijheid, L. Bouchard, A.A. Baccarelli, L.A. Croen, W. Karmaus, D. Anderson, M. de Vries, S. Seberty, J. Kere, R. Karlsson, S.H. Arshad, E. Hämaläinen, M.N. Routledge, D.I. Boomsma, A.P. Feinberg, C.J. Newschaffer, E. Govarts, M. Moisse, M.D. Fallin, E. Melén, A.M. Prentice, Meta-analysis of epigenome-wide association studies in neonates reveals widespread differential DNA methylation associated with birthweight, *Nat. Commun.* (2019) 1893.
- [12] H.T. den Dekker, K. Burrows, J.F. Felix, L.A. Salas, I. Nedeljkovic, J. Yao, S. Rifas-Shiman, C. Ruiz-Arenas, N. Amin, M. Bustamante, D.L. DeMeo, A.J. Henderson, C. G. Howe, M.F. Hivert, M.A. Ikram, J.C. de Jongste, L. Lahousse, P.R. Mandaviya, J. B. van Meurs, M. Pinart, G.C. Sharp, L. Stolck, A.G. Uitterlinden, J.M. Anto, A. A. Litonjua, C.V. Breton, G.G. Brusselle, J. Sunyer, G.D. Smith, C.L. Relton, V.W. V. Jaddoe, L. Duijts, Newborn DNA-methylation, childhood lung function, and the risks of asthma and COPD across the life course, *Eur. Respir. J.* 53 (2019), <https://doi.org/10.1183/13993003.0179-2018>. Print 2019 Apr.
- [13] S.J. van Dijk, T.J. Peters, M. Buckley, J. Zhou, P.A. Jones, R.A. Gibson, M. Makrides, B.S. Muhlhauser, P.L. Molloy, DNA methylation in blood from neonatal screening cards and the association with BMI and insulin sensitivity in early childhood, *Int. J. Obes.* 42 (2018) 28–35.
- [14] S.E. Reese, C.J. Xu, H.T. den Dekker, M.K. Lee, S. Sikdar, C. Ruiz-Arenas, S. K. Merid, F.I. Rezwan, C.M. Page, V. Ulleamar, P.E. Melton, S.S. Oh, I.V. Yang, K. Burrows, C. Soderhall, D.D. Jima, L. Gao, R. Arathimos, L.K. Kupers, M. Wielscher, P. Rzehak, J. Lahti, C. Laprise, A.M. Madore, J. Ward, B.D. Bennett, T. Wang, D.A. Bell, BIOS consortium, J.M. Vonk, S.E. Haberg, S. Zhao, R. Karlsson, E. Hollams, D. Hu, A.J. Richards, A. Bergstrom, G.C. Sharp, J.F. Felix, M. Bustamante, O. Gruziova, R.L. Maguire, F. Gilliland, N. Baiz, E.A. Nohr, E. Corpeleijn, S. Seberty, W. Karmaus, V. Grote, E. Kajantie, M.C. Magnus, A. K. Orqvist, C. Eng, A.H. Liu, I. Kull, V.W.V. Jaddoe, J. Sunyer, J. Kere, C. Hoyo, I. Annesi-Maesano, S.H. Arshad, B. Koletzko, B. Brunekreef, E.B. Binder, K. Raikonen, E. Reischl, J.W. Holloway, M.R. Jarvelin, H. Snieder, N. Kazmi, C. V. Breton, S.K. Murphy, G. Pershagen, J.M. Anto, C.L. Relton, D.A. Schwartz, E. G. Burchard, R.C. Huang, W. Nystrand, C. Almqvist, A.J. Henderson, E. Melén, L. Duijts, G.H. Koppelman, S.J. London, Epigenome-wide meta-analysis of DNA methylation and childhood asthma, *J. Allergy Clin. Immunol.* 143 (2019) 2062–2074.
- [15] L. Carrel, H.F. Willard, X-inactivation profile reveals extensive variability in X-linked gene expression in females, *Nature* 434 (2005) 400–404.
- [16] R.M. Adkins, F. Thomas, F.A. Tylavsky, J. Krushkal, Parental ages and levels of DNA methylation in the newborn are correlated, *BMC Med. Genet.* 12 (2011) 47.
- [17] R.M. Adkins, J. Krushkal, F.A. Tylavsky, F. Thomas, Racial differences in gene-specific DNA methylation levels are present at birth, *Birth Defects Res A Clin. Mol. Teratol.* 91 (2011) 728–736.
- [18] P. Yousefi, K. Huen, V. Davé, L. Barcellos, B. Eskenazi, N. Holland, Sex differences in DNA methylation assessed by 450 K BeadChip in newborns, *BMC Genom.* 16 (2015) 911.
- [19] M. Suderman, A. Simpkin, G. Sharp, T. Gaunt, O. Lyttleton, W. McArdle, S. Ring, G. Davey Smith, C. Relton, Sex-associated autosomal DNA methylation differences are wide-spread and stable throughout childhood, *bioRxiv.*, 2017, 118265.
- [20] A.K. Zozack, E. Colicino, A.C. Just, R.O. Wright, A.A. Baccarelli, R.J. Wright, A. G. Lee, Associations between infant sex and DNA methylation across umbilical cord blood, artery, and placenta samples, *Epigenetics* (2021) 1–18.
- [21] N.S. McCarthy, P.E. Melton, G. Cadby, S. Yazar, M. Franchina, E.K. Moses, D. A. Mackey, A.W. Hewitt, Meta-analysis of human methylation data for evidence of sex-specific autosomal patterns, *BMC Genom.* 15 (2014) 981.
- [22] C. Fuke, M. Shimabukuro, A. Petronis, J. Sugimoto, T. Oda, K. Miura, T. Miyazaki, C. Ogura, Y. Okazaki, Y. Jinno, Age related changes in 5-methylcytosine content in human peripheral leukocytes and placentas: an HPLC-based study, *Ann. Hum. Genet.* 68 (2004) 196–204.
- [23] M. Inoshita, S. Numata, A. Tajima, M. Kinoshita, H. Umehara, H. Yamamori, R. Hashimoto, I. Imoto, T. Ohmori, Sex differences of leukocytes DNA methylation adjusted for estimated cellular proportions, *Biol. Sex Differ.* 6 (2015) 11–17, eCollection 2015.
- [24] J. Liu, M. Morgan, K. Hutchison, D.C. Vince, A study of the influence of sex on genome wide methylation, *PLoS One* 5 (2010), e10028.
- [25] P.B. Marco, M.D. Eske, J.W. Daniel, E. Strengman, E. Janson, E.S. Iris, S.K. René, A. O. Roel, The relationship of DNA methylation with age, gender and genotype in twins and healthy controls, *PLoS One* 4 (2009), e6767.
- [26] P. Singmann, D. Shem-Tov, S. Wahl, H. Grallert, G. Fiorito, S.Y. Shin, K. Schramm, P. Wolf, S. Kunze, Y. Baran, S. Guarrera, P. Vineis, V. Krogh, S. Panico, R. Tumino, A. Kretschmer, C. Gieger, A. Peters, H. Prokisch, C.L. Relton, G. Matullo, T. Illig, M. Waldenberger, E. Halperin, Characterization of whole-genome autosomal differences of DNA methylation between men and women, *Epigenet. Chromatin* 8 (2015) 43, 43, eCollection 2015.
- [27] E. Martin, L. Smeester, P.A. Bommarito, M.R. Grace, K. Boggess, K. Kuban, M. R. Karagas, C.J. Marsit, T.M. O’Shea, R.C. Fry, Sexual epigenetic dimorphism in the human placenta: implications for susceptibility during the prenatal period, *Epigenomics* 9 (2017) 267–278.
- [28] A.M. Inkster, V. Yuan, C. Konwar, A.M. Matthews, C.J. Brown, W.P. Robinson, A cross-cohort analysis of autosomal DNA methylation sex differences in the term placenta, *Biol. Sex Differ.* 12 (2021) 1–14.
- [29] L. Dearden, S.G. Bouret, S.E. Ozanne, Sex and gender differences in developmental programming of metabolism, *Mol. Metab.* 15 (2018) 8–19.
- [30] R. Arathimos, R. Granell, J. Henderson, C.L. Relton, K. Tilling, Sex discordance in asthma and wheeze prevalence in two longitudinal cohorts, *PLoS One* 12 (2017), e0176293.
- [31] M. Muenchhoff, P.J.R. Goulder, Sex differences in pediatric infectious diseases, *J. Infect. Dis.* 209 (Suppl. 3) (2014) 120.
- [32] E. Melén, A. Bergström, I. Kull, C. Almqvist, N. Andersson, A. Asaranoj, M.P. Borres, A. Georgellis, G. Pershagen, M. Westman, M. van Hage, N. Ballardini, Male sex is strongly associated with IgE-sensitization to airborne but not food allergens: results up to age 24 years from the BAMSE birth cohort, *Clin. Transl. Allergy* 10 (2020) 15. -w. eCollection 2020.
- [33] T. Green, S. Flash, A.L. Reiss, Sex differences in psychiatric disorders: what we can learn from sex chromosome aneuploidies, *Neuropsychopharmacology* 44 (2019) 9–21.
- [34] I. Capone, P. Marchetti, P.A. Ascierto, W. Malorni, L. Gabriele, Sexual dimorphism of immune responses: a new perspective in cancer immunotherapy, *Front. Immunol.* 9 (2018) 552.
- [35] J.B. Rubin, J.S. Lagas, L. Broestl, J. Sponagel, N. Rockwell, G. Rhee, S.F. Rosen, S. Chen, R.S. Klein, P. Imoukhuede, J. Luo, Sex differences in cancer mechanisms, *Biol. Sex Differ.* 11 (2020) 17.
- [36] J.F. Felix, B.R. Joubert, A.A. Baccarelli, G.C. Sharp, C. Almqvist, I. Annesi-Maesano, H. Arshad, N. Baiz, M. Bakermans-Kranenburg, K.M. Bakulski, E. B. Binder, L. Bouchard, C.V. Breton, B. Brunekreef, K.J. Brunst, E.G. Burchard, M. Bustamante, L. Chatzi, M. Cheng Munthe-Kaas, E. Corpeleijn, D. Czamara, D. Dabelea, G. Davey Smith, P. De Boever, L. Duijts, T. Dwyer, C. Eng, B. Eskenazi, T.M. Everson, F. Falahi, M.D. Fallin, S. Farchi, M.F. Fernandez, L. Gao, T.R. Gaunt, A. Ghanous, M.W. Gillman, S. Gonseth, V. Grote, O. Gruziova, S.E. Häberg, Z. Herceg, M. Hivert, N. Holland, J.W. Holloway, C. Hoyo, D. Hu, R. Huang, K. Huen, M. Jarvelin, D.D. Jima, A.C. Just, M.R. Karagas, R. Karlsson, W. Karmaus, K.J. Keckris, J. Kere, M. Kogevinas, B. Koletzko, G.H. Koppelman, L.K. Kupers, C. Ladd-Acosta, J. Lahti, N. Lambrechts, S.A.S. Langie, R.T. Lie, A.H. Liu, M. C. Magnus, P. Magnus, R.L. Maguire, C.J. Marsit, W. McArdle, E. Melén, P. Melton, S.K. Murphy, T.S. Nawrot, L. Nisticò, E.A. Nohr, B. Nordlund, W. Nystrand, S.S. Oh, E. Oken, C.M. Page, P. Perron, G. Pershagen, C. Pizzi, M. Plusquin, K. Raikonen, S. E. Reese, E. Reischl, L. Richiardi, S. Ring, R.P. Roy, P. Rzehak, G. Schoeters, D. A. Schwartz, S. Seberty, H. Snieder, T.I.A. Sørensen, A.P. Starling, J. Sunyer, J. A. Taylor, H. Tiemeier, V. Ulleamar, M. Vafeiadi, M.H. Van Ijzendoorn, J.M. Vonk, A. Vriens, M. Vrijheid, P. Wang, J.L. Wiemels, A.J. Wilcox, R.J. Wright, C. Xu, Z. Xu, I.V. Yang, P. Yousefi, H. Zhang, W. Zhang, S. Zhao, G. Agha, C.L. Relton, V. W.V. Jaddoe, S.J. London, Cohort profile: pregnancy and childhood epigenetics (PACE) consortium, *Int. J. Epidemiol.* (2017).
- [37] M. Bibikova, B. Barnes, C. Tsan, V. Ho, B. Klotzle, J.M. Le, D. Delano, L. Zhang, G. P. Schroth, K.L. Gunderson, High density DNA methylation array with single CpG site resolution, *Genomics* 98 (2011) 288–295.
- [38] M.J. Aryee, A.E. Jaffe, H. Corrada-Bravo, C. Ladd-Acosta, A.P. Feinberg, K. D. Hansen, R.A. Irizarry, Minfi: a flexible and comprehensive bioconductor package for the analysis of infinium DNA methylation microarrays, *Bioinformatics* 30 (2014) 1363–1369.
- [39] W.E. Johnson, C. Li, A. Rabinovic, Adjusting batch effects in microarray expression data using empirical bayes methods, *Biostatistics* 8 (2007) 118–127.
- [40] B.K. Andrews, SV. FlowSorted.CordBlood.450k: Illumina 450k Data on Sorted Cord Blood Cells, R Package Version 1.12.0, 2019.
- [41] A.E. Jaffe, FlowSorted.blood.450k: Illumina Human Methylation Data on Sorted Blood Cell Populations, R Package Version 1.22.0., 2019.
- [42] W.N. Venables, B.D. Ripley, *Modern Applied Statistics with S*, Springer-Verlag, New York, 2002.
- [43] W. Huber, V.J. Carey, R. Gentleman, S. Anders, M. Carlson, B.S. Carvalho, H. C. Bravo, S. Davis, L. Gatto, T. Girke, R. Gottardo, F. Hahne, K.D. Hansen, R. A. Irizarry, M. Lawrence, M.I. Love, J. MacDonald, V. Obenchain, A. Oleś K, H. Pages, A. Reyes, P. Shannon, G.K. Smyth, D. Tenenbaum, L. Waldron, M. Morgan, Orchestrating high-throughput genomic analysis with bioconductor, *Nat. Methods* 12 (2015) 115–121.
- [44] C.T.R., R: A Language And Environment For Statistical Computing, 3.4.1., 2017.
- [45] Y. Chen, M. Lemire, S. Choufani, D.T. Butcher, D. Grafodatskaya, B.W. Zanke, S. Gallinger, T.J. Hudson, R. Weksberg, Discovery of cross-reactive probes and polymorphic CpGs in the illumina infinium HumanMethylation450 microarray, *Epigenetics* 8 (2013) 203–209.
- [46] J.P. Higgins, S.G. Thompson, Quantifying heterogeneity in a meta-analysis, *Stat. Med.* 21 (2002) 1539–1558.
- [47] M. Kanehisa, Y. Sato, M. Kawashima, M. Furumichi, M. Tanabe, KEGG as a reference resource for gene and protein annotation, *Nucleic Acids Res.* 44 (2016) D457–D462.
- [48] E.I. Boyle, S. Weng, J. Gollub, H. Jin, D. Botstein, J.M. Cherry, G. Sherlock, GO:: TermFinder—open source software for accessing gene ontology information and finding significantly enriched gene ontology terms associated with a list of genes, *Bioinformatics* 20 (2004) 3710–3715.
- [49] J. Maksimovic, A. Oshlack, B. Phipson, Gene set enrichment analysis for genome-wide DNA methylation data, *Genome Biol.* 22 (2021) 1–26.
- [50] J. Piñero, À. Bravo, N. Queralt-Rosinach, A. Gutiérrez-Sacristán, J. Deu-Pons, E. Centeno, J. García-García, F. Sanz, L.I. Furlong, DisGeNET: a comprehensive platform integrating information on human disease-associated genes and variants, *Nucleic Acids Res.* 45 (2017) D83–D839.
- [51] G. Yu, L. Wang, G. Yan, Q. He, DOSE: an R/bioconductor package for disease ontology semantic and enrichment analysis, *Bioinformatics* 31 (2015) 608–609.
- [52] D. Aprile, F. Fruscione, S. Baldassari, M. Fadda, D. Ferrante, A. Falace, E. Buhler, J. Sartorelli, A. Represa, P. Baldelli, F. Benfenati, F. Zara, A. Fassio, TBC1D24 regulates axonal outgrowth and membrane trafficking at the growth cone in rodent and human neurons, *Cell Death Differ.* 26 (2019) 2464–2478.
- [53] S. Balestrini, M. Milh, C. Castiglioni, K. Lüthy, M.J. Finelli, P. Verstreken, A. Cardon, B.G. Stražičar, J.L. Holder Jr., G. Lesca, M.M. Mancardi, A.L. Poulat, G. M. Repetto, S. Banka, L. Bilo, L.E. Birkeland, F. Bosch, K. Brockmann, J.H. Cross, D. Doummar, T.M. Félix, F. Giuliano, M. Hori, I. Hüning, H. Kayserili, U. Kini, M.

- M. Lees, G. Meenakshi, L. Mewasingh, A.T. Pagnamenta, S. Peluso, A. Mey, G. M. Rice, J.A. Rosenfeld, J.C. Taylor, M.M. Troester, C.M. Stanley, D. Ville, M. Walkiewicz, A. Falace, A. Fassio, J.R. Lemke, S. Biskup, J. Tardif, N. F. Ajeawung, A. Tolun, M. Corbett, J. Geetz, Z. Afawi, K.B. Howell, K.L. Oliver, S. F. Berkovic, I.E. Scheffer, F.A. de Falco, P.L. Oliver, P. Striano, F. Zara, P. M. Campeau, S.M. Sisodiya, TBC1D24 genotype-phenotype correlation: epilepsies and other neurologic features, *Neurology* 87 (2016) 77–85.
- [54] H. Loke, V. Harley, J. Lee, Biological factors underlying sex differences in neurological disorders, *Int. J. Biochem. Cell Biol.* 65 (2015) 139–150.
- [55] D.S. Reddy, The neuroendocrine basis of sex differences in epilepsy, *Pharmacol. Biochem. Behav.* 152 (2017) 97–104.
- [56] L. Statello, C. Guo, L. Chen, M. Huarte, Gene regulation by long non-coding RNAs and its biological functions, *Nat. Rev. Mol. Cell Biol.* (2020) 1–23.
- [57] W. Xu, G. Zhou, H. Wang, Y. Liu, B. Chen, W. Chen, C. Lin, S. Wu, A. Gong, M. Xu, Circulating lncRNA SNHG11 as a novel biomarker for early diagnosis and prognosis of colorectal cancer, *Int. J. Cancer* 146 (2020) 2901–2912.
- [58] S. Bitarafan, M. Yari, M.A. Broumand, S.M.H. Ghaderian, M. Rahimi, R. Mirfakhraie, F. Azizi, M.D. Omrani, Association of increased levels of lncRNA H19 in PBMCs with risk of coronary artery disease, *Cell J. Yakhteh* 20 (2019) 564.
- [59] H. Fallah, I. Azari, S.M. Neishabouri, V.K. Oskooei, M. Taheri, S. Ghafouri-Fard, Sex-specific up-regulation of lncRNAs in peripheral blood of patients with schizophrenia, *Sci. Rep.* 9 (2019) 1–8.
- [60] M. Majewska, A. Lipka, L. Paukszto, J.P. Jastrzebski, M. Gowkielewicz, M. Jozwik, M.K. Majewski, Preliminary RNA-seq analysis of long non-coding RNAs expressed in human term placenta, *Int. J. Mol. Sci.* 19 (2018) 1894.
- [61] C. Ober, Y. Gilad, D.A. Loisel, Sex-specific genetic architecture of human disease, *Nat. Rev. Genet.* 9 (2008) 911–922.
- [62] R. Shah, D.C. Newcomb, Sex bias in asthma prevalence and pathogenesis, *Front. Immunol.* 9 (2018) 2997.
- [63] C.C. Whitacre, Sex differences in autoimmune disease, *Nat. Immunol.* 2 (2001) 777–780.
- [64] M.C. Kander, Y. Cui, Z. Liu, Gender difference in oxidative stress: a new look at the mechanisms for cardiovascular diseases, *J. Cell. Mol. Med.* 21 (2017) 1024–1032.
- [65] S.J. Uekert, G. Akan, M.D. Evans, Z. Li, K. Roberg, C. Tisler, D. Dasilva, E. Anderson, R. Gangnon, D.B. Allen, J.E. Gern, R.F. Lemanske, Sex-related differences in immune development and the expression of atopy in early childhood, *J. Allergy Clin. Immunol.* 118 (2006) 1375–1381.
- [66] Carmen P. McLean, Anu Asnaani, Brett T. Litz, Stefan G. Hofmann, Gender differences in anxiety disorders: prevalence, course of illness, comorbidity and burden of illness, *J. Psychiatr. Res.* 45 (2011) 1027–1035.
- [67] M. Maschietto, L.C. Bastos, A.C. Tahira, E.P. Bastos, V.L.V. Euclides, A. Brentani, G. Fink, A. De Baumont, A. Felipe-Silva, R.P.V. Francisco, Sex differences in DNA methylation of the cord blood are related to sex-bias psychiatric diseases, *Sci. Rep.* 7 (2017) 44547.
- [68] A.K. Halladay, S. Bishop, J.N. Constantino, A.M. Daniels, K. Koenig, K. Palmer, D. Messinger, K. Pelphrey, S.J. Sanders, A.T. Singer, J.L. Taylor, P. Szatmari, Sex and gender differences in autism spectrum disorder: summarizing evidence gaps and identifying emerging areas of priority, *Mol. Autism* 6 (2015) 36.
- [69] J.J. Bauermeister, P.E. Shrout, L. Chávez, M. Rubio-Stipec, R. Ramírez, L. Padilla, A. Anderson, P. García, G. Canino, ADHD and gender: are risks and sequela of ADHD the same for boys and girls? *J. Child Psychol. Psychiatry* 48 (2007) 831–839.
- [70] M.J. Essex, J.M. Armstrong, W. Thomas Boyce, C. Hertzman, L.L. Lam, M.A. N. Sarah, M.S. Kobor, Epigenetic vestiges of early developmental adversity: childhood stress exposure and DNA methylation in adolescence, *Child Dev.* 84 (2013) 58–75.
- [71] D.A. Armstrong, C. Lesueur, E. Conradt, B.M. Lester, C.J. Marsit, Global and gene-specific DNA methylation across multiple tissues in early infancy: implications for children's health research, *FASEB J.* 28 (2014) 2088–2097.
- [72] K.M. Bakulski, J.I. Feinberg, S.V. Andrews, J. Yang, S. Brown, S.L. McKenney, F. Witter, J. Walston, A.P. Feinberg, M.D. Fallin, DNA methylation of cord blood cell types: applications for mixed cell birth studies, *Epigenetics* 11 (2016) 354–362.