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ORIGINAL RESEARCH

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Population trajectories and age-dependent associations of obesity risk factors with body mass index from childhood to adolescence across European regions: A two-cohort study

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Summary

Objective: To investigate population trajectories of behavioural risk factors of obesity from childhood to adolescence and their associations with body mass index (BMI) in children across European regions.

Methods: Data were harmonised between the European multi-centre IDEFICS/I.Family and the Amsterdam Born Children and their Development Cohort. Participants were aged 2.0–9.9 and 5.0–7.5 years at baseline, respectively, and were followed until age 18 years. Behavioural risk factors of interest included diet, physical activity, media use and sleep. Mixed effects models were used for statistical analyses to account for repeated measurements taken from the same child.

Results: The study included a total of 14 328 individuals: 4114, 4582, 3220 and 2412 participants from Northern, Southern, Eastern Europe and Amsterdam, respectively. Risk factor means and prevalences changed with age, but the trajectories were mostly similar across regions. Almost no associations between behavioural factors and BMI were found at the age of 6 years. At 11 years, daily sugar-sweetened foods consumption, use of active transport, sports club membership and longer nocturnal sleep duration were negatively associated with BMI in most regions; positive associations were found with media use. Most associations at 11 years of age persisted to 15 years.

Conclusions: Whilst population trajectories of media use and nocturnal sleep duration are similar across European regions, those of other behavioural risk factors like active transport and daily vegetable consumption differ. Also, associations between behavioural risk factors and BMI become stronger with age and show similar patterns across regions.

KEYWORDS

adolescent, child, epidemiology, multicenter, prevalence, risk factors

1 | INTRODUCTION

Whilst some countries have reached a plateau, many others continue to show a trend of increasing average body mass index (BMI) amongst children up to the age of 18 years since the 1970s.[1,2] Children with overweight or obesity have an increased risk of physical illnesses, mental disorders and early death.[2–4] Children are especially vulnerable to an obesogenic environment due to their limited understanding of what healthy behaviours are, and their dependence on their parents and environment.[2,5,6] Whereas weight gain is a result of energy intake greater than energy expenditure, the environment plays a complex role on physiological pathways that influence satiety and behaviours to attain this balance.[7]

Regional characteristics such as genetics, culture, climate and infrastructure can explain differences in weight status between populations.[2,8] Previous works found region and ethnicity to be associated with variations in, for example, diet,[9–11] physical activity,[12,13] maternal BMI,[14–18] parental educational level,[14,19] feeding patterns,[14,18] weight perception[17] and height.[20] Additionally, the influence of obesity risk factors on children is complicated by changes that occur with age and development.[2] This means that children may be more vulnerable to certain risk factors during specific transition periods.[21–27] Despite the extensive list of risk factors for obesity,[2,27] less is known about the ages at which risk factors show their most detrimental effects. This information is crucial for guiding the implementation of effective strategies in sensitive time windows during the early life course and in different environments.

We performed an explorative study on various risk factors of obesity in a multi-centre population cohort from medium-sized cities across European regions and, for comparison, a cohort from a large city in the Netherlands. More specifically, we investigated population trajectories of behavioural risk factors from childhood to adolescence across European regions, and investigated whether these risk factors are associated with BMI in an age-dependent manner.

2 | METHODS

2.1 | Participant data

The present study is based on data from two cohorts: the IDEFICS (Identification and Prevention of Dietary- and Lifestyle-Induced Health Effects in Children and Infants)/I.Family (Investigating the determinants of food choice, lifestyle and health in European children, adolescents and their parents) and ABCD (Amsterdam Born Children and their Development) studies. The IDEFICS/I.Family study is a multi-centre population-based cohort of children from 8 European countries: Belgium, Cyprus, Estonia, Germany, Hungary, Italy, Sweden and Spain.[28,29] The focus is on investigating the aetiology of diseases related to diet and behaviour in children and their families. The baseline examination wave (W0), conducted from September 2007 to June 2008, included 16 229 children aged 2.0–9.9 years. Two years later, the first follow-up wave (W1) took place, enrolling 2544 new participants. Two subsequent follow-up waves were conducted 6 (W2) and 14 years (W3) after baseline. Questionnaire assessments and physical examinations were performed using standardised procedures across all countries. At W3, BMI was self-reported because no physical examinations were performed. Ethical approval was obtained from the institutional review boards of all 8 study centres. Written informed consent for examinations and sample collection was provided by the parents and children aged 12 years and older; younger children provided oral consent.

The ABCD study is a cohort of Dutch children who were followed up since pregnancy.[30] The aim of ABCD is to investigate the effects of perinatal factors on health outcomes up to young adulthood. W0, W1 and W2 took place at around the ages of 6 years (range = 5.0–7.5 years), 12 years (10.6–13.7 years) and 16 years (15.1–17.2 years), respectively. At each wave, each parent filled in questionnaires about their own behaviours and the health and development of their child (fathers were only sent questionnaires at W1 and W2). The children were asked to fill in questionnaires about their own behaviours from W1 onwards. Growth data was measured at W0 and W1 when children underwent physical examinations by the ABCD health check. This was complemented by youth healthcare registration measurements until the age of approximately 13 years.[31] Growth data from W2 was self-reported. A total of 8266 pregnant women residing in Amsterdam filled out the pregnancy questionnaire between January 2003 and March 2004, of whom 7050 (85%) gave permission for follow-up.

2.2 | Variables and harmonisation

All variables shared between the IDEFICS/I.Family and ABCD were considered for harmonisation, excluding questions from the Strength and Difficulties Questionnaire because some questions were not assessed in IDEFICS/I.Family. Based on the expert opinion of three researchers (A.S., C.B. and T.V.), variables with potential for harmonisation were selected and converted into common formats. In most cases, this required a re-categorisation combining certain categories or assignment of continuous values to certain categories. Variables that were considered comparable between studies (with or without transformations in one or both cohorts) and which were available at three time points in one study and no fewer than two time points in the other were included in the present study. A description of all variables is given in the supplement.

2.2.1 | Outcome

The primary outcome of this study is BMI, a common measure for weight status in epidemiological studies. This was measured in W0–W2 in IDEFICS/I.Family, and self-reported in W3. BMI was also converted into age- and sex-specific *z*-scores and was categorised into children with underweight, normal weight, overweight and obesity according to the extended International Obesity Task Force criteria.[32]

2.2.2 | Risk factors

The exposures of interest were known and suspected behavioural risk factors of obesity-related to (i) diet, namely water consumption (times/day), sweetened drinks consumption (times/day, including artificially sweetened drinks and sweetened milk), daily vegetable consumption (yes vs. no), daily fruit consumption (yes vs. no), daily sugar-sweetened foods consumption (yes vs. no) and vegetarian diet (yes vs. no); (ii) physical activity, namely active transport to school (yes vs. no; walking or cycling at least 4 days per week) and sports club membership (yes vs. no); (iii) media use, namely television (TV) and personal computer (PC) media use (h/day) and (iv) nocturnal sleep duration (h/night). Data on sugar-sweetened food consumption and sports club membership were not available for W1 of the ABCD cohort.

2.2.3 | Covariates

The following variables were considered as potential confounders: (i) parental characteristics, namely mother's BMI (kg/m^2), father's BMI (kg/m^2), highest parental ISCED (International Standard Classification of Education, high vs. low/medium)[33] and migrant background (both parents vs. one parent vs. neither parent); (ii) family structure/vulnerabilities, namely number of children in household, only child (yes vs. no), single parent (yes vs. no) and parental divorce (yes vs. no) and (iii) peri-/post-natal factors, namely smoking during pregnancy (yes vs. no), alcohol consumption during pregnancy (yes vs. no), maternal age at birth (years), child's sex (male vs. female), birthweight (g), preterm birth (yes vs. no), C-section delivery (yes vs. no), exclusive breastfeeding duration (no exclusive breastfeeding vs. <3 months vs. 3–<6 months vs. ≥ 6 months) and age at introduction to new foods (<4 months vs. 4 to <6 months vs. ≥ 6 months before consuming foods other than breast milk and formula milk). A more detailed description of the variables used is provided in the supplement.

IDEFICS was designed as a controlled intervention trial from W0 to W1. To account for possible effects the intervention may have had in the long run, all models are based on the IDEFICS/I.Family data were adjusted for children living in the control or intervention region (binary variable). However, as the IDEFICS intervention did not show any effects on body fatness or behavioural factors in the total study group, we consider it unlikely that the IDEFICS intervention will have affected our results.[34–36]

2.3 | Data set preparation

Examination waves were excluded from our analysis if one of the following criteria applied: age less than 2 years, age greater than 18 years, missing participant's BMI, missing all dietary variables (i.e., vegetables, fruits, added sugar foods, water and sweetened drinks consumption frequencies), and fewer than two observations per participant (after applying the other criteria). The final study samples are subsequently referred to as 'ABCD cohort' and 'IDEFICS/I.Family cohort'. Figure 1 depicts the selection process leading to the final study samples.

Multiple imputations with 10 iterations per imputation were used to handle missing data using the 'mice' package's default method for each data type.[37] This was performed independently for the IDEFICS/I.Family and ABCD cohorts. A wide data set format (based on each wave) of the data set was used for this to improve estimates, including all variables in the algorithm.[38] This procedure was repeated 100 times to create 100 complete data sets.

2.4 | Statistical analysis

All analyses were performed using statistical program R version 4.1.2.[39] For the IDEFICS/I.Family cohort, the subsequent analyses were stratified by three regions: Northern (Belgium, Sweden, Germany), Southern (Cyprus, Italy, Spain) and Eastern Europe (Estonia, Hungary). Though located in Northern Europe, the ABCD cohort was treated as a separate fourth region—Amsterdam—to enable comparisons between cohorts as well as between medium-sized cities (approximately 18 000–400 000 inhabitants) and a large city

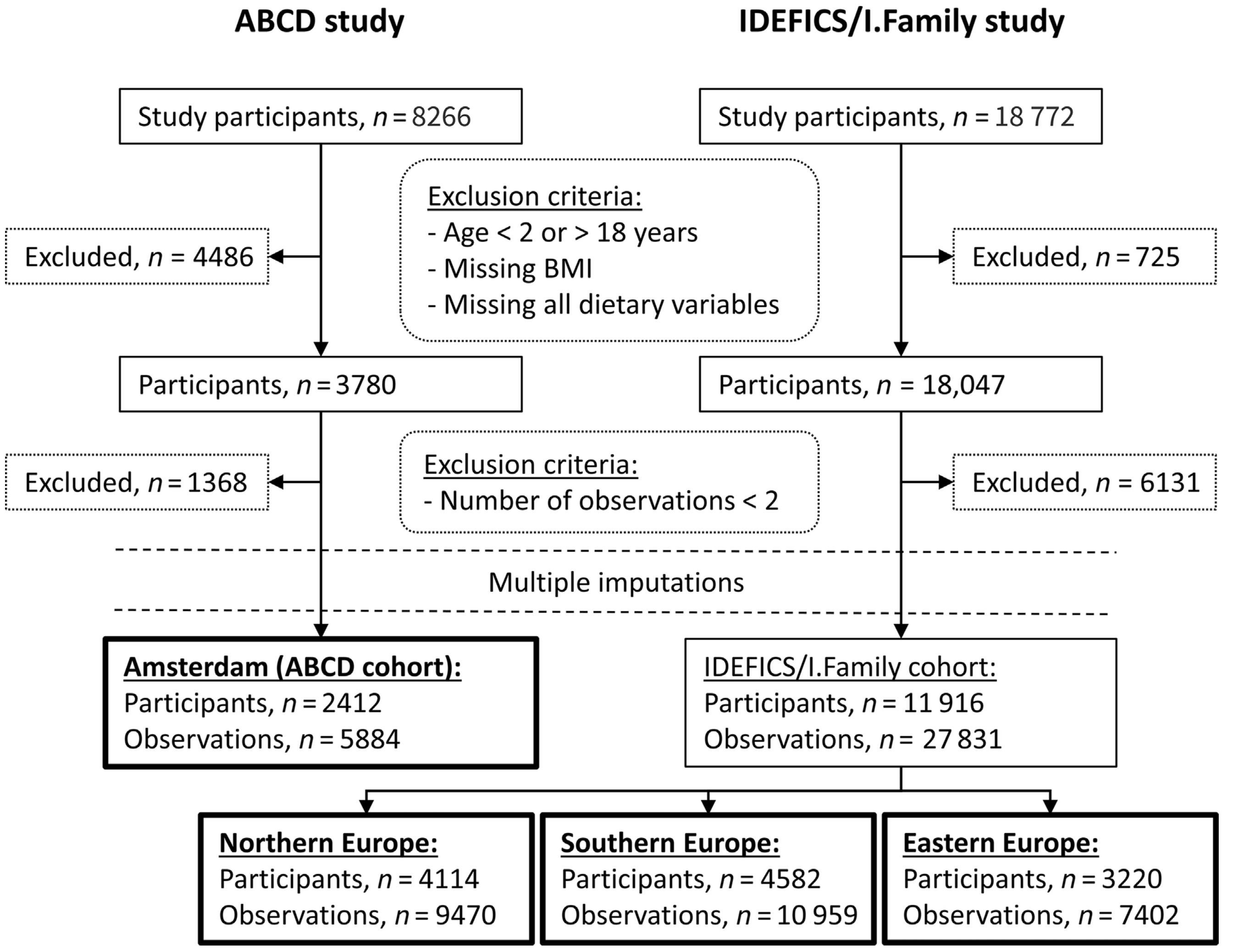

FIGURE 1 Participant selection flowchart. BMI, body mass index.

(>700 000 inhabitants). Continuous variables were reported as means and standard deviations, and categorical variables were described using frequencies and percentages. Histograms of continuous variables were visually inspected and deemed to be normally distributed.

Mixed effects models were used to account for the repeated measurements taken within the same child. In the main analysis, the mean (continuous variables) or prevalence (binary variables) of each risk factor across age were estimated, including subject-specific random intercepts. The dependent variable for each model was a risk factor, and the independent variables were three polynomials of age (i.e., age, age^2 and age^3), sex and the three interaction terms between each pair (i.e., age·sex, age^2·sex and age^3·sex). Linear mixed models were used when the risk factor was continuous, and binomial generalised linear mixed models were used for binary risk factors. A BOBYQA (Bound Optimisation BY Quadratic Approximation) optimiser was used for the latter to handle convergence issues.[40] Results are displayed in plots stratified by sex with 99% confidence intervals.

In a second analysis, we estimated the age-specific associations between each behavioural risk factor and BMI, as well as associations between the well-established risk factors parental ISCED and parental BMI and children's BMI. Linear mixed models were used with BMI as the dependent variable. The independent variables included the three polynomials of age, sex, their three interaction terms, a risk factor and three interaction terms between each polynomial of age and risk factor (i.e., age·risk factor, age^2·risk factor and age^3·risk factor) as a minimal adjustment set. All additional confounders derived from a directed acyclic graph (see Figure S1) were added as independent variables for full model adjustment.[41] Table S1 lists all corresponding adjustment sets. The coefficients with 99% confidence intervals for the association of each risk factor with BMI at the ages of 6, 11 and 15 years were reported; this was done based on reparametrised analyses with age centred at 6, 11 and 15 years, respectively.

All analyses were performed on all 100 imputed data sets, the results of which were pooled. Sensitivity analyses were also performed on a cohort where, in addition to the other exclusion criteria, observations with underweight status were excluded. The purpose was to assess whether associations between risk factors and BMI differ depending on whether most changes in BMI occur in children with underweight compared to children without.

3 | RESULTS

The descriptive statistics at baseline before and after imputations are summarised in Table S3 and Table 1, respectively. The IDEFICS/I.Family cohort consisted of 11 916 participants with 27 831 observations over all examination waves, and the ABCD cohort consisted of 2412 participants with 5884 observations (Figure 1). The frequency of missing data in the final IDEFICS/I.Family (max. 34.2%) and ABCD cohorts (max. 39.7%) are reported in Table S2. Several differences between cohorts were noted (Table 1). ABCD had a greater proportion of children whose

TABLE 1 Characteristics of the study population at baseline (one imputed data set).

Variable	Amsterdam, $n = 2412$	Northern Europe, $n = 4114$	Southern Europe, $n = 4582$	Eastern Europe, $n = 3220$
Continuous variables, mean (SD)				
Age (years)	6.1 (2.3)	5.9 (1.9)	6.2 (1.7)	6.2 (2.1)
Birthweight (g)	3504 (536)	3397 (596)	3183 (552)	3451 (579)
Mother's BMI (kg/m^2)	23.5 (3.9)	24.2 (4.3)	23.9 (4.3)	23.6 (4.4)
Father's BMI (kg/m^2)	24.8 (3.0)	26.0 (3.7)	27.2 (4.1)	26.9 (4.5)
Number of children in household	2.2 (0.9)	2.2 (0.9)	2.2 (0.9)	2.0 (0.9)
Water consumption (times/day)	1.5 (1.1)	2.4 (1.4)	3.6 (0.9)	2.7 (1.4)
Sweetened drinks consumption (times/day)	2.1 (1.2)	1.8 (1.8)	1.8 (1.5)	2.0 (1.7)
Media use (h/day)	1.4 (0.9)	1.5 (0.9)	1.7 (1.1)	1.8 (1.1)
Nocturnal sleep duration (h/night)	10.5 (0.9)	10.9 (0.9)	10.0 (1.0)	9.6 (1.0)
BMI *z*-score	−0.2 (1.1)	0.1 (1.0)	0.7 (1.2)	0.1 (1.1)
Categorical variables, frequency (%)				
Female sex (yes)	1175 (48.7)	2060 (50.1)	2325 (50.7)	1570 (48.8)
High parental ISCED (yes)	1836 (76.1)	2429 (59.0)	1867 (40.7)	1703 (52.9)
Migrant background	-	-	-	-
Neither parent	1724 (71.5)	3380 (82.2)	3706 (80.9)	3091 (96.0)
One parent	462 (19.2)	321 (7.8)	637 (13.9)	105 (3.3)
Both parents	226 (9.4)	413 (10.0)	239 (5.2)	24 (0.7)
Smoking during pregnancy	-	-	-	-
No smoking	2240 (92.9)	3518 (85.5)	3898 (85.1)	2909 (90.3)
<1 cigarette per day	59 (2.4)	299 (7.3)	381 (8.3)	226 (7.0)
≥1 cigarette per day	113 (4.7)	297 (7.2)	303 (6.6)	85 (2.6)
Alcohol during pregnancy (yes)	729 (30.2)	1073 (26.1)	1167 (25.5)	944 (29.3)
Preterm birth (yes)	212 (8.8)	464 (11.3)	539 (11.8)	335 (10.4)
C-section delivery (yes)	316 (13.1)	816 (19.8)	1683 (36.7)	600 (18.6)
Exclusive breastfeeding duration	-	-	-	-
No exclusive breastfeeding	379 (15.7)	1364 (33.2)	1621 (35.4)	551 (17.1)
<3 months	773 (32.0)	893 (21.7)	978 (21.3)	831 (25.8)
3 to <6 months	899 (37.3)	1213 (29.5)	1228 (26.8)	827 (25.7)
≥6 months	361 (15.0)	644 (15.7)	755 (16.5)	1011 (31.4)
Age at introduction to new foods[a]	-	-	-	-
<4 months	123 (5.1)	639 (15.5)	226 (4.9)	494 (15.3)
4 to <6 months	892 (37.0)	2093 (50.9)	1855 (40.5)	1275 (39.6)
≥6 months	1397 (57.9)	1382 (33.6)	2501 (54.6)	1451 (45.1)
Being an only child (yes)	383 (15.9)	646 (15.7)	809 (17.7)	884 (27.5)
Single parent (yes)	175 (7.3)	324 (7.9)	948 (20.7)	399 (12.4)
Parents divorced (yes)	176 (7.3)	498 (12.1)	184 (4.0)	529 (16.4)
Daily vegetable consumption (yes)	1619 (67.1)	3261 (79.3)	2090 (45.6)	2050 (63.7)
Daily fruit consumption (yes)	1571 (65.1)	2816 (68.4)	3113 (67.9)	2027 (63.0)

(Continues)

TABLE 1 (Continued)

Variable	Amsterdam, *n* = 2412	Northern Europe, *n* = 4114	Southern Europe, *n* = 4582	Eastern Europe, *n* = 3220
Daily sugar-sweetened foods consumption (yes)	1764 (85.8)	2148 (52.2)	2146 (46.8)	1611 (50.0)
Vegetarian diet (yes)	80 (3.3)	34 (0.8)	20 (0.4)	13 (0.4)
Active transport to school (yes)[b]	1102 (45.7)	1673 (40.7)	1204 (26.3)	1240 (38.5)
Sports club member (yes)	1147 (55.8)	2207 (53.6)	1967 (42.9)	1301 (40.4)
With overweight or obesity (yes)	186 (7.7)	452 (11.0)	1351 (29.5)	452 (14.0)

Note: Continuous variables are reported as means with SDs in brackets. Categorical variables are reported as frequencies with percentages in brackets.
Abbreviations: BMI, body mass index; SD, standard deviation.
[a]Foods other than breast milk and formula milk.
[b]Walking or cycling at least 4 days per week.

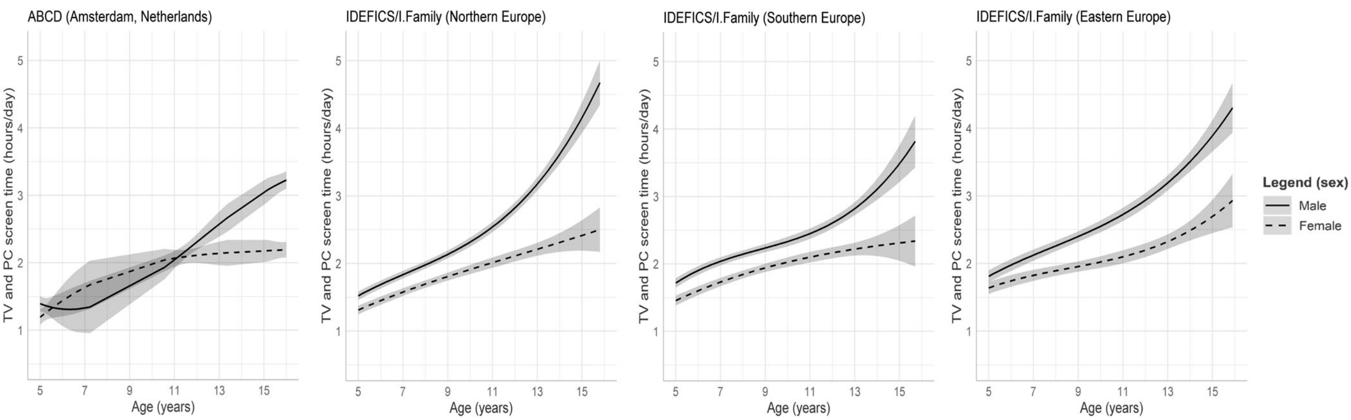

FIGURE 2 Mean television (TV) and personal computer (PC) media use across age and European regions, stratified by sex. Shaded areas represent 99% confidence intervals, where darker shades indicate an overlap of confidence intervals from the two lines.

parents had high ISCED (76.1% in ABCD vs. 50.3% in IDEFICS/I.Family) and migrant backgrounds (28.6% vs. 14.6%), and a lower mean paternal BMI (24.8 vs. 26.7 kg/m^2), fewer C-section deliveries (13.1% vs. 26.0%) and fewer single-parent households (7.6% vs. 14.0%).

3.1 | Population trajectories

The age-dependent means and prevalences of behavioural risk factors are given in Figures 2 and 3, and S2–S9. Compared to the IDEFICS/I.Family cohort, the ABCD participants reported less water consumption (mean = 2.9 vs. 1.5 times/day, respectively) and more often sugar-sweetened foods on a daily basis at baseline (49.2% vs. 85.8%) (Figures S2 and S6). Children in Amsterdam also had a higher proportion of vegetarians across all ages (0.5% vs. 3.3% at baseline), increasing beyond 10% amongst female teenagers (Figure S7). Except for sports club membership, males more often engaged in unhealthier behaviours than females (i.e., more frequent intake of sweetened drinks, less frequent intake of fruits and vegetables, less likely to be vegetarian and more media use).

Most behaviours showed similar trends across the four regions. For example, media usage, sweetened drinks consumption frequency and the proportion of sports club members increased with age (Figures 2, S3 and S8). In contrast, the proportion of daily fruit consumers, the proportion of daily sugar-sweetened foods consumers, and nocturnal sleep duration decreased with age (Figures S5, S6 and S9).

Other risk factors displayed more inter-regional variation, the most notable being the proportion of active transport users (Figure 3). Active transport usage was highest in Amsterdam—approaching 100% amongst teenagers—and lowest in Southern Europe—remaining stable at 10%. Whilst this was similar between the sexes, an exception was that active transport was used more amongst male teenagers in Eastern Europe.

The prevalence of daily vegetable consumers also varied across regions (Figure S4), with the smallest fluctuation with age in Northern Europe (between 81% and 86% across all ages), the steepest increase with age in Southern Europe (mean at age 5 years = 40% vs. mean at age 15 years = 78%), a more gradual increase with age in Eastern Europe (mean at age 5 years = 64% vs. mean at age 15 years = 74%) and a decrease with age in Amsterdam (mean at age 5 years = 70% vs. mean at age 15 years = 59%).

3.2 | Associations with BMI

The average BMI, average BMI *z*-score and the proportion of children with overweight or obesity with age in each region are shown in

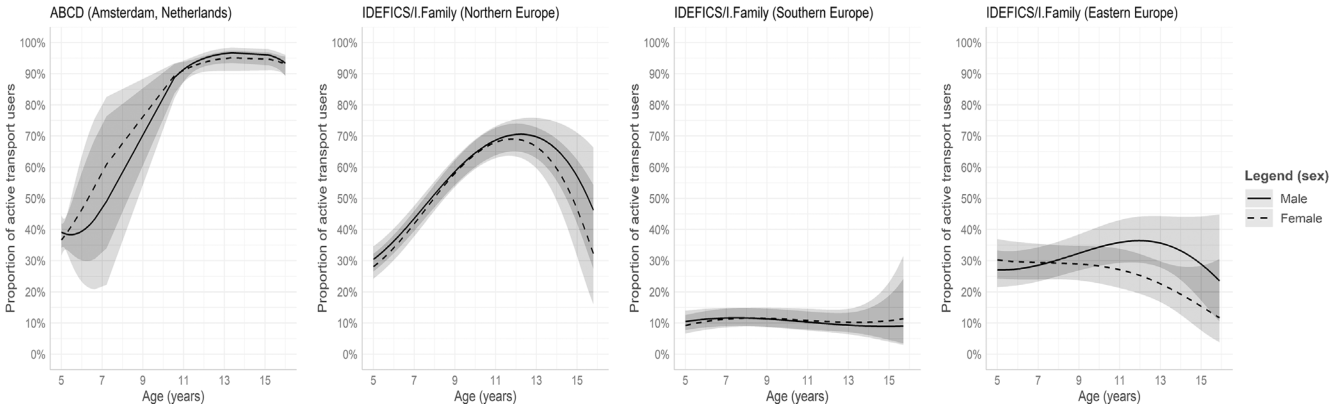

FIGURE 3 Proportion of active transport users across age and European regions, stratified by sex. Shaded areas represent 99% confidence intervals, where darker shades indicate an overlap of confidence intervals from the two lines.

TABLE 2 Fully adjusted associations between risk factors and body mass index (BMI) at the age of 6 years.

Risk factor	Amsterdam Coefficient (LCI–UCI)	Northern Europe Coefficient (LCI–UCI)	Southern Europe Coefficient (LCI–UCI)	Eastern Europe Coefficient (LCI–UCI)
Highest parental ISCED[a] (high)	−0.41 (−1.00 to 0.18)	−0.07 (−0.22 to 0.08)	**−0.45 (−0.66 to −0.23)**	−0.10 (−0.33 to 0.13)
Mother's BMI[b] (kg/m^2)	0.04 (−0.02 to 0.10)	**0.05 (0.03–0.07)**	**0.07 (0.05–0.09)**	**0.07 (0.05–0.10)**
Father's BMI[b] (kg/m^2)	0.03 (−0.06 to 0.11)	0.00 (−0.02 to 0.01)	−0.01 (−0.03 to 0.01)	−0.01 (−0.03 to 0.02)
Water consumption[c] (times/day)	−0.10 (−0.30 to 0.10)	−0.01 (−0.05 to 0.03)	0.06 (−0.02 to 0.14)	0.01 (−0.06 to 0.07)
Sweetened drinks consumption[c] (times/day)	−0.05 (−0.22 to 0.11)	−0.04 (−0.08 to 0.00)	−0.05 (−0.10 to 0.00)	0.02 (−0.03 to 0.07)
Daily vegetable consumption[c] (yes)	−0.09 (−0.62 to 0.43)	0.13 (−0.01 to 0.28)	0.04 (−0.11 to 0.19)	−0.04 (−0.22 to 0.14)
Daily fruit consumption[c] (yes)	0.34 (−0.17 to 0.86)	0.02 (−0.11 to 0.15)	0.04 (−0.12 to 0.20)	−0.01 (−0.19 to 0.17)
Daily sugar-sweetened foods consumption[c] (yes)	−0.97 (−2.36 to 0.41)	−0.02 (−0.14 to 0.10)	**−0.17 (−0.32 to −0.02)**	0.07 (−0.10 to 0.24)
Vegetarian diet[c] (yes)	0.07 (−0.95 to 1.09)	−0.02 (−0.80 to 0.76)	0.43 (−0.63 to 1.49)	−0.33 (−1.69 to 1.02)
Active transport to school[d] (yes)	**−0.71 (−1.29 to −0.12)**	−0.03 (−0.16 to 0.09)	−0.11 (−0.29 to 0.08)	−0.06 (−0.26 to 0.13)
Sports club member[d] (yes)	0.25 (−0.65 to 1.14)	0.11 (−0.01 to 0.23)	0.11 (−0.04 to 0.27)	0.01 (−0.17 to 0.19)
Media use[e] (h/day)	−0.17 (−0.37 to 0.03)	−0.04 (−0.11 to 0.03)	−0.03 (−0.10 to 0.04)	0.02 (−0.07 to 0.10)
Nocturnal sleep duration[f] (h/night)	**0.24 (0.03–0.46)**	−0.04 (−0.11 to 0.03)	−0.07 (−0.14 to 0.01)	−0.03 (−0.13 to 0.07)

Note: Results from linear mixed models. The IDEFICS/I.Family cohort was divided into Northern (Belgium, Sweden and Germany), Southern (Cyprus, Italy and Spain) and Eastern Europe (Estonia and Hungary). Coefficients whose 99% confidence intervals do not include zero are indicated in bold.
Abbreviations: BMI, body mass index; LCI, lower 99% confidence interval; UCI, upper 99% confidence interval.
[a]Adjusted for: age, sex and migrant background.
[b]Adjusted for: age, sex, migrant background, highest parental ISCED, number of children in household, only child, single parent and parental divorce.
[c]Adjusted for: age, sex, migrant background, highest parental ISCED, mother's BMI, father's BMI, smoking during pregnancy, alcohol during pregnancy, birthweight, maternal age at birth, preterm birth, C-section delivery, exclusive breastfeeding duration and age at introduction to new food items, number of children in household, only child, single parent, parental divorce, nocturnal sleep duration, media use and active transport to school.
[d]Adjusted for: age, sex, migrant background, highest parental ISCED, mother's BMI, father's BMI, number of children in household, only child, single parent, parental divorce and media use.
[e]Adjusted for: age, sex, migrant background, highest parental ISCED, mother's BMI, father's BMI, number of children in household, only child, single parent and parental divorce.
[f]Adjusted for: age, sex, migrant background, highest parental ISCED, number of children in household, only child, single parent, parental divorce, media use and active transport to school.

Figures S10–S12. The fully adjusted effect estimates obtained for the associations between the behavioural risk factors and BMI at the ages of 6, 11 and 15 years are reported in Tables 2–4, respectively. Across all regions and ages, each increase of the mother's BMI by 1 kg/m^2 increased the child's BMI by 0.04–0.21 kg/m^2 on average. At the ages of 11 and 15 years, the child's BMI was also positively associated with father's BMI and negatively associated with high parental ISCED.

TABLE 3 Fully adjusted associations between risk factors and body mass index (BMI) at the age of 11 years.

Risk factor	Amsterdam Coefficient (LCI–UCI)	Northern Europe Coefficient (LCI–UCI)	Southern Europe Coefficient (LCI–UCI)	Eastern Europe Coefficient (LCI–UCI)
Highest parental ISCED[a] (high)	**−1.13 (−1.49 to −0.76)**	**−0.80 (−0.98 to −0.63)**	**−1.23 (−1.46 to −0.99)**	**−0.51 (−0.76 to −0.27)**
Mother's BMI[b] (kg/m^2)	**0.17 (0.14–0.21)**	**0.18 (0.16–0.20)**	**0.20 (0.17–0.22)**	**0.18 (0.15–0.20)**
Father's BMI[b] (kg/m^2)	**0.14 (0.10–0.19)**	**0.11 (0.10–0.13)**	**0.11 (0.09–0.13)**	**0.09 (0.07–0.12)**
Water consumption[c] (times/day)	0.01 (−0.09 to 0.12)	0.05 (0.00–0.11)	0.00 (−0.08 to 0.08)	**0.08 (0.01–0.16)**
Sweetened drinks consumption[c] (times/day)	0.01 (−0.08 to 0.10)	−0.01 (−0.05 to 0.03)	0.01 (−0.04 to 0.05)	−0.04 (−0.08 to 0.01)
Daily vegetable consumption[c] (yes)	−0.28 (−0.55 to 0.00)	−0.12 (−0.30 to 0.06)	**−0.30 (−0.48 to −0.12)**	−0.05 (−0.25 to 0.15)
Daily fruit consumption[c] (yes)	0.01 (−0.25 to 0.28)	−0.07 (−0.23 to 0.08)	**−0.21 (−0.39 to −0.03)**	0.02 (−0.17 to 0.22)
Daily sugar-sweetened foods consumption[c] (yes)	−1.06 (−3.45 to 1.33)	**−0.22 (−0.37 to −0.07)**	**−0.22 (−0.40 to −0.04)**	**−0.36 (−0.55 to −0.17)**
Vegetarian diet[c] (yes)	0.05 (−0.49 to 0.59)	0.41 (−0.23 to 1.06)	0.42 (−0.76 to 1.60)	−1.12 (−2.45 to 0.21)
Active transport to school[d] (yes)	**−0.56 (−0.99 to −0.12)**	−0.05 (−0.20 to 0.10)	**−0.38 (−0.59 to −0.17)**	**0.29 (0.08–0.50)**
Sports club member[d] (yes)	0.43 (−1.31 to 2.17)	**−0.30 (−0.47 to −0.12)**	**−0.32 (−0.50 to −0.14)**	**−0.26 (−0.47 to −0.05)**
Media use[e] (h/day)	**0.15 (0.04–0.27)**	**0.12 (0.06–0.18)**	**0.18 (0.11–0.25)**	**0.13 (0.06–0.21)**
Nocturnal sleep duration[f] (h/night)	0.08 (−0.09 to 0.24)	**−0.10 (−0.18 to −0.02)**	**−0.15 (−0.25 to −0.05)**	**−0.16 (−0.29 to −0.03)**

Note: Results from linear mixed models. The IDEFICS/I.Family cohort was divided into Northern (Belgium, Sweden and Germany), Southern (Cyprus, Italy and Spain) and Eastern Europe (Estonia and Hungary). Coefficients whose 99% confidence intervals do not include zero are indicated in bold.
Abbreviations: BMI, body mass index; LCI, lower 99% confidence interval; UCI, upper 99% confidence interval.
[a]Adjusted for: age, sex and migrant background.
[b]Adjusted for: age, sex, migrant background, highest parental ISCED, number of children in household, only child, single parent and parental divorce.
[c]Adjusted for: age, sex, migrant background, highest parental ISCED, mother's BMI, father's BMI, smoking during pregnancy, alcohol during pregnancy, birthweight, maternal age at birth, preterm birth, C-section delivery, exclusive breastfeeding duration and age at introduction to new food items, number of children in household, only child, single parent, parental divorce, nocturnal sleep duration, media use and active transport to school.
[d]Adjusted for: age, sex, migrant background, highest parental ISCED, mother's BMI, father's BMI, number of children in household, only child, single parent, parental divorce and media use.
[e]Adjusted for: age, sex, migrant background, highest parental ISCED, mother's BMI, father's BMI, number of children in household, only child, single parent and parental divorce.
[f]Adjusted for: age, sex, migrant background, highest parental ISCED, number of children in household, only child, single parent, parental divorce, media use and active transport to school.

Regarding behavioural risk factors at the age of 6 years, active transport in Amsterdam and daily sugar-sweetened food consumption in Southern Europe were found to be negatively associated with BMI, and nocturnal sleep duration was positively associated with BMI in Amsterdam (Table 2). At 11 years, positive associations were found for water consumption and media use whereas negative associations were found for daily vegetable consumption, daily sugar-sweetened foods consumption, sports club membership and nocturnal sleep duration (Table 3). For active transport, negative associations were found in Amsterdam and Southern Europe and a positive association was found in Eastern Europe. Only a few associations persisted until the age of 15 years, namely water consumption, daily sugar-sweetened foods consumption, active transport, sports club membership, media use and nocturnal sleep duration (Table 4).

Fully adjusted associations did not differ markedly from the minimally adjusted associations (Tables S4–S6). Associations found from the sensitivity analyses—excluding 1655/14 328 (11.6%) children with underweight at W0—were markedly similar to their respective results from the main analyses (Figure S13, Tables S7–S14).

4 | DISCUSSION

4.1 | Population trajectories

We performed an explorative analysis on 10 known and suspected risk factors of obesity in children from four European regions within two cohorts. Whilst most regions showed similar trends in means and prevalences with age, considerable regional differences were found for the proportion of active transport users and daily vegetable consumers. Media use, nocturnal sleep duration and the proportion of sports club members varied the least across regions. Except for being more likely to be sports club members, males more often engaged in unhealthy behaviours than females.[42–47] In line with the literature, males consumed more sweetened drinks,[46] had more screen time,[42,44,45] were less likely to eat vegetables and fruits every day[44,45] and were less often vegetarian.[40–45]

Some risk factors from Amsterdam stand out as compared to the IDEFICS/I.Family cohort regions. The high proportion of ABCD participants using an active form of transport can be attributable to the Netherlands having the world's best cycling infrastructure.[48]

TABLE 4 Fully adjusted associations between risk factors and body mass index (BMI) at the age of 15 years.

Risk factor	Amsterdam Coefficient (LCI–UCI)	Northern Europe Coefficient (LCI–UCI)	Southern Europe Coefficient (LCI–UCI)	Eastern Europe Coefficient (LCI–UCI)
Highest parental ISCED[a] (high)	**−0.69 (−1.16 to −0.22)**	**−1.67 (−2.14 to −1.20)**	**−0.91 (−1.53 to −0.29)**	**−0.68 (−1.19 to −0.16)**
Mother's BMI[b] (kg/m^2)	**0.21 (0.17–0.26)**	**0.21 (0.16–0.25)**	**0.15 (0.09–0.21)**	**0.20 (0.14–0.25)**
Father's BMI[b] (kg/m^2)	**0.14 (0.07–0.20)**	**0.14 (0.10–0.19)**	**0.09 (0.02–0.15)**	**0.13 (0.08–0.19)**
Water consumption[c] (times/day)	**0.19 (0.04–0.34)**	−0.06 (−0.22 to 0.10)	0.07 (−0.21 to 0.36)	0.06 (−0.11 to 0.23)
Sweetened drinks consumption[c] (times/day)	0.03 (−0.09 to 0.15)	0.09 (0.00–0.19)	−0.06 (−0.20 to 0.07)	**0.14 (0.05–0.23)**
Daily vegetable consumption[c] (yes)	−0.01 (−0.40 to 0.38)	−0.37 (−0.88 to 0.15)	−0.09 (−0.76 to 0.58)	0.40 (−0.16 to 0.95)
Daily fruit consumption[c] (yes)	0.01 (−0.38 to 0.39)	−0.47 (−0.95 to 0.01)	−0.39 (−1.03 to 0.26)	0.24 (−0.28 to 0.77)
Daily sugar-sweetened foods consumption[c] (yes)	−0.10 (−0.67 to 0.48)	0.15 (−0.35 to 0.65)	**−0.99 (−1.64 to −0.35)**	−0.23 (−0.74 to 0.29)
Vegetarian diet[c] (yes)	−0.11 (−0.78 to 0.56)	0.21 (−1.15 to 1.56)	3.03 (−2.11 to 8.17)	−0.58 (−3.33 to 2.16)
Active transport to school[d] (yes)	−0.11 (−0.70 to 0.48)	**−0.60 (−1.09 to −0.10)**	**−0.89 (−1.60 to −0.18)**	0.10 (−0.43 to 0.62)
Sports club member[d] (yes)	0.41 (−0.24 to 1.07)	**−0.83 (−1.33 to −0.33)**	**−0.88 (−1.52 to −0.24)**	−0.37 (−0.90 to 0.16)
Media use[e] (h/day)	**0.16 (0.03–0.28)**	**0.29 (0.15–0.43)**	0.03 (−0.19 to 0.25)	**0.17 (0.03–0.31)**
Nocturnal sleep duration[f] (h/night)	−0.15 (−0.30 to 0.01)	−0.08 (−0.31 to 0.15)	0.09 (−0.22 to 0.40)	**−0.36 (−0.65 to −0.08)**

Note: Results from linear mixed models. The IDEFICS/I.Family cohort was divided into Northern (Belgium, Sweden and Germany), Southern (Cyprus, Italy and Spain) and Eastern Europe (Estonia and Hungary). Coefficients whose 99% confidence intervals do not include zero are indicated in bold.
Abbreviations: BMI, body mass index; LCI, lower 99% confidence interval; UCI, upper 99% confidence interval.
[a]Adjusted for: age, sex and migrant background.
[b]Adjusted for: age, sex, migrant background, highest parental ISCED, number of children in household, only child, single parent and parental divorce.
[c]Adjusted for: age, sex, migrant background, highest parental ISCED, mother's BMI, father's BMI, smoking during pregnancy, alcohol during pregnancy, birthweight, maternal age at birth, preterm birth, C-section delivery, exclusive breastfeeding duration and age at introduction to new food items, number of children in household, only child, single parent, parental divorce, nocturnal sleep duration, media use and active transport to school.
[d]Adjusted for: age, sex, migrant background, highest parental ISCED, mother's BMI, father's BMI, number of children in household, only child, single parent, parental divorce and media use.
[e]Adjusted for: age, sex, migrant background, highest parental ISCED, mother's BMI, father's BMI, number of children in household, only child, single parent and parental divorce.
[f]Adjusted for: age, sex, migrant background, highest parental ISCED, number of children in household, only child, single parent, parental divorce, media use and active transport to school.

Regarding fluids consumption, sweetened drinks consumption frequency was similar across regions but not water consumption frequency. Whereas drinking less water is likely to be compensated by drinking more sweetened beverages,[49,50] this pattern was not clear in our findings. The higher water consumption in Southern Europe may be attributable to the warmer climate and the observed larger body sizes. Less water consumption before the age of 11 in Amsterdam is likely an underestimation compared to the other European regions. This is because a different questionnaire was used for W0 as opposed to later waves: water consumption was measured as times per week instead of glasses per day, respectively.

The population trajectories of most behaviours shifted in the transition from childhood to adolescence. A possible causal explanation is that children obtain more social contacts around that age, thus their behaviours become more likely to be shaped by their peers than by their parents or siblings.[51,52] However, differences may also be partly related to children starting to fill in the questionnaires by themselves at approximately 12 years of age. Despite both self-reports and proxy reports being prone to social desirability bias, a discrepancy usually remains between the two.[53–55]

4.2 | Associations with BMI

Consistent with previous literature,[2,5–7,22,31,56] parental ISCED and parental BMI were strongly associated with child's BMI regardless of the adjustment set. The associations of maternal BMI with the child's BMI were stronger than for the paternal BMI across the reported ages (i.e., 6, 11 and 15 years). This may be because most children spend more time with their mothers and imitate behaviours from them,[5] and because women are more often responsible for meal preparation.[57,58] Moreover, physiological adaptations might already occur in the intra-uterine period (foetal programming) as a consequence of the adverse metabolic or inflammatory environment.[59] Regardless, members within the same household tend to have similar weight status given shared genes and behaviours.

Amongst behavioural risk factors, almost no associations were found with BMI at the age of 6 years. At 11 and 15 years of age, negative associations were found between BMI and sweetened drinks consumption frequency, daily sugar-sweetened foods consumption, active transport, sports club membership, less media use and longer nocturnal sleep duration in most regions. We note that nocturnal sleep duration changed from being positively associated with BMI (in Amsterdam) at the age of 6 years to becoming negatively associated at 11 and 15 years of age. This suggests that too much sleep as well as too little sleep is associated with BMI,[25,60] though we did not consider other possible factors such as sleep quality, time of going to bed and time of getting up.

The classification of sugary foods and drinks as risk factors for obesity is well established,[61] so the negative associations found require an explanation. One possibility is that sugar-sweetened foods are difficult to classify and may be unreliably reported. Moreover, foods considered unhealthy may be particularly prone to misreporting due to socially desirable answering behaviour. Additionally, total caloric intake was unavailable. Another possible explanation is that children who are considered to be overweight by their parents or themselves may have more (self-)imposed dietary restrictions than others.[62]

A notable finding was that active transport was positively associated with BMI in Eastern Europe at age 11. A possible explanation is that, in Eastern Europe, active transport is a proxy for lower income and the inability to afford other modes of transport.[48] The observation that active transport becomes less popular amongst females beyond puberty whilst remaining viable for males may be related to the perception of the built environment.[63] For example, well-lit streets at night are associated with active transport amongst females.

The sensitivity analyses produced results equivalent to those from the main analyses. This suggests that the associations between behavioural risk factors and BMI do not differ when stratified into BMI categories. However, it is possible that the exclusion of observations with underweight status was insufficient to noticeably affect the results.

Overall, the effect sizes of the associations found between each behavioural risk factor and BMI can be interpreted as small.[64] Therefore, an implication of this exploratory study is that behavioural risk factors should not be considered as independent from other factors: targeting individual risk factors is expected to offer limited benefits. The causal pathway from upstream factors to behaviour and from behaviour to BMI is complex and unique to each individual, also dependent on genetic and environmental factors which were not available for this study.[2,5–8] Consideration of the systemic conditions that shape health-related behaviours—socioeconomic status in particular—would likely improve the effectiveness of preventing children from gaining too much weight.[56]

4.3 | Strengths and limitations

Strengths of this study are its large sample size, the inclusion of many risk factors, and the use of data from various European countries and from two independent studies. Whilst Amsterdam would typically be grouped with Northern Europe, the proportions of migrants and highly educated inhabitants, for example, are greater in Amsterdam; these differences may be associated with city size. The finding that most population risk factor trajectories were similar indicates that harmonisation was performed well and that many behaviours may be universally promising targets for interventions.

Some limitations should be taken into consideration. In this study, we investigated the age-specific associations between behavioural risk factors and BMI. Despite following a longitudinal modelling approach based on mixed effects models (accounting for correlations amongst repeated measurements taken from the same child), the associations between the behavioural risk factors and BMI at the different ages should be interpreted cross-sectionally because the exposures and outcomes were assessed at the same ages.

Data collection was not performed in a consistent manner throughout the ABCD examination waves. Unlike the IDEFICS/I.Family data, the ABCD data were not interspersed across all ages. In combination with the smaller sample size, the gaps between ages 7–10 and 12–14 years resulted in less smooth population trajectories as compared to the trajectories estimated based on the IDEFICS/I.Family data. However, to obtain stable estimates for the associations between behavioural risk factors and BMI, associations were only estimated at ages for which there was sufficient data amongst both cohorts.

Our measure of media use was only based on TV and PC screen time. Currently, the estimated percentages of 9- to 16-year-olds with internet access who used smartphones daily in the studied countries ranged from 76% in Spain to 87% in Estonia.[65] With the increase of mobile phones and other digital media being used amongst children, it may be considered a limitation that smartphone exposure was not available for this study. Whilst this may be negligible for the first and second assessment waves, our reported media use may be an underestimation of total media usage in the later examination waves.[66]

5 | CONCLUSIONS

The population means and prevalences of most behavioural risk factors of obesity generally change with age. Some risk factors trajectories are consistent across European regions, such as media use and nocturnal sleep duration, whilst other trajectories differ considerably between regions, such as active transport and daily vegetable consumption. Overall, associations between behavioural risk factors and BMI become stronger with age and show similar patterns across regions. Though often reproduced across European regions and across cohorts with different data collection methods, the strength of association between each behavioural risk factor and BMI can be considered small. Associations that were inconsistent with the literature or varied across regions require further research to determine whether the collected data is an adequate proxy of the risk factor that is trying to be measured. Whilst all well-established healthy behaviours should be encouraged, regional and socioeconomic factors should be considered on an individual level when mitigating each risk factor.

AUTHOR CONTRIBUTIONS

Anton Schreuder, Claudia Börnhorst and Toomas Veidebaum contributed to conceptualisation. Anton Schreuder and Claudia Börnhorst contributed to the methodology. Anton Schreuder and Claudia Börnhorst contributed to the formal analysis. Claudia Börnhorst, Maike Wolters, Toomas Veidebaum, Michael Tornaritis, Elida Sina, Paola

Russo, Luis A. Moreno, Denes Molnar, Lauren Lissner, Stefaan De Henauw, Wolfgang Ahrens and Toomas Veidebaum contributed to data acquisition. Anton Schreuder, Claudia Börnhorst and Toomas Veidebaum contributed to the first draft of the manuscript. All authors contributed to reviewing and editing the manuscript. All authors have read and agreed to the final version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

No conflict of interest was declared.

DATA AVAILABILITY STATEMENT

The IDEFICS and I.Family studies data that support the findings of this study are not publicly available because they contain information that could compromise the quality of the study, but the data sharing committee is willing to receive requests. Interested researchers can contact the IDEFICS and I.Family consortia (http://www.ideficsstudy.eu/Idefics/ and http://www.ifamilystudy.eu/) to discuss the possibilities for data access. The individual ABCD study data are not available for a public repository for ethical reasons but can be made available to other researchers for purposes of reproducing results or for collaboration. Researchers wishing to apply for the data can contact the project leader of the ABCD study (abcd@amsterdamumc.nl).

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Additional supporting information can be found online in the Supporting Information section at the end of this article.

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