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Association of Impulsivity With Food, Nutrients, and Fitness in a Longitudinal Birth Cohort Study

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Abstract

Background: Impulsivity is a psychiatric vulnerability factor strongly associated with substance abuse but also with unhealthy diet. Whether these associations extend to specific nutrients is largely unknown. Therefore, we investigated the longitudinal association between diet, cardiorespiratory fitness, and 2 impulsivity dimensions in a representative sample of south Estonian adolescents and young adults. Impulsivity and dietary intake were measured 3 times in 2 birth cohorts at regular intervals in individuals aged 15 to 33 years.

Methods: The sample included 2 birth cohorts of the longitudinal Estonian Children Personality Behaviour and Health Study. The analytic sample size consisted of 2883 observations (56.4% females). The primary outcomes were adaptive and maladaptive impulsivity scores measured by an original 24-item Likert-type questionnaire. Impulsivity scores were predicted from the food diaries data converted into nutrient categories. A linear mixed-effects approach was used to model the time dependence between observations.

Results: Lower maladaptive impulsivity was associated with higher cardiorespiratory fitness ($\beta = -.07$; 95% CI = –0.12; –0.03). Higher maladaptive impulsivity was associated with lower dietary intake of zinc ($\beta = -.10$; –0.15; –0.06) and vegetables ($\beta = -.04$; –0.07; –0.01) and higher intake of sodium ($\beta = .06$; 0.02; 0.10). Vitamin B6 was positively associated with adaptive impulsivity ($\beta = .04$; 0.01; 0.07). Additionally, some of the adjusted models showed significant but weak associations with selenium, alcohol, fish, and cereal products.

Conclusions: Food choice may affect the neurochemistry and therefore regulate the manifestations of impulsivity. We identified associations between several (micro)nutrients and maladaptive impulsivity.

Keywords: Impulsivity, diet, longitudinal birth cohort, cardiorespiratory fitness, zinc, vitamin B6

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Significance Statement

Impulsivity is a complex trait manifesting, e.g., in our decision-making. Which food to consume is one of such choices that people make several times each day. So far, the relationship between diet and impulsivity has been mostly studied in connection with clinical manifestation of eating disorders, substance abuse, and obesity. The present report is the first longitudinal study, to our knowledge, conducted on a representative birth cohort sample of adolescents and young adults that investigates the associations between 2 impulsivity dimensions, dietary intake, and cardiorespiratory fitness. Both adaptive and maladaptive impulsivity were related to diet, while the associations were specific to the aspect of impulsivity; additionally, maladaptive impulsivity was associated with lower cardiorespiratory fitness. Higher adaptive impulsivity was associated with increased vitamin B6 levels in the dietary intake. These associations suggest that the manifestation of maladaptive impulsivity can be managed via physical activity and micronutrient supplementation.

Introduction

Impulsivity is “a range of actions which are poorly conceived, prematurely expressed, unduly risky or inappropriate to the situation and that often result in undesirable consequences” (Daruna and Barnes, 1993). In psychiatry, impulsivity is included in diagnostic criteria for a variety of disorders, such as alcohol and substance abuse, mood and anxiety disorders, attention-deficit/hyperactivity disorder (ADHD), eating disorders, pathological gambling, and certain personality disorders (Berg et al., 2015). In psychology, impulsivity is considered the behavioral manifestation of several personality traits (Whiteside and Lynam, 2001; Zuckerman and Glicksohn, 2016). Genome-wide association studies confirm that dimensions of impulsivity form intricate relationships with psychiatric endophenotypes and show genetic overlap with ADHD and substance use disorders (Sanchez-Roige et al., 2019). A variety of distinct aspects of impulsivity have been proposed and studied, especially in clinical contexts. In the current study, however, we follow the concept of Dickman (1990) and Hans Eysenck (Eysenck, 2004) by parsing impulsivity into dysfunctional and functional dimensions. The social and personal consequences of the dysfunctional impulsive actions are usually negative, whereas manifestations of functional impulsivity are mostly beneficial. Rapid, error-prone information processing lies at the core of both types of impulsivities, and an individual’s other personality traits determine the optimality of the outcomes (Dickman, 1990). The 2 types of impulsivities were measured with the original Adaptive and maladaptive impulsivity scale (AMIS) that extends the functional vs dysfunctional impulsivity model and has been successfully used for, for example, distinguishing the impulsivity profiles by the type of traffic violations (Paaver et al., 2006). Hereafter, we refer to the dysfunctional and functional dimensions of impulsivity as maladaptive and adaptive in specific cases of the impulsivity measures obtained with the AMIS questionnaire.

The genetic architecture of impulsivity is unclear as heritability of impulsive traits (40%–60%) is order(s) of magnitude larger that has been estimated from the genotyped single nucleotide polymorphisms (<10%) (Sanchez-Roige et al., 2019). In addition to genetics, the environment also plays a role, which changes with age. In principle, personality traits are malleable and can be shaped by prolonged experience or effort (Hudson and Fraley, 2015; Hudson et al., 2020). Transition from a more regimented environment of adolescence where diet and physical activity are governed by family and school into adulthood increases the risks associated with impulsive decision-making, such as overeating or risky behaviors, and tightens a putative feedback loop between personality and environment. Food choices and levels of physical exercise are manifestations of personality and decision-making that, in turn, affect biochemistry and formation of behavioral habits. In practical terms, as both nutrition and physical exercise affect brain neurochemistry, they can be considered as auxiliary tools to pharmacological methods for controlling excessive impulsivity. However, the empirical validation of the idea in the general population is scarce (Fleig et al., 2011). Studies conducted in rats show that diets high in sugar or fat can make the animals more impulsive independently of the weight gain (Adams et al., 2015; Steele et al., 2017; Garman et al., 2021). In humans, people who consume more sugar, but not fat, were found to have a stronger preference for large rewards and a lower tolerance of the delayed rewards (Steele et al., 2021). However, laboratory findings have a limited scope, and their clinical relevance is often low. The relationship between diet and impulsivity has been studied mainly along 2 paths: overeating/unhealthy food choices and (micro) nutrient deficiencies. The associations between higher impulsivity and unhealthy nutritional choices have been found in several studies. For example, overeating and greater consumption of Western-style diet, sugar-sweetened and alcoholic beverages, snacks, and take-away food have all been linked to higher impulsivity (Jasinska et al., 2012; Lumley et al., 2016; Bénard et al., 2019).

Some studies have found an association of higher impulsivity with increased energy intake and higher body mass index (BMI) (Jasinska et al., 2012; VanderBroek-Stice et al., 2017; Bénard et al., 2019). Research along the second path tries to identify the link between the bioavailability of a particular micronutrient and impulsive behavior. Increased plasma tryptophan following breakfast was associated with changes in the individual propensity for risky decisions, and this effect was modulated by BMI (Liu et al., 2021). A study conducted on a small group of students further found that higher tryptophan intake was associated with lower scores on 2 impulsivity subscales (Javelle et al., 2021a). Additionally, several studies link vitamin D deficiency with the increased propensity to act impulsively (Grudet et al., 2014; Wrzosek et al., 2018; Todisco et al., 2020).

Cardiorespiratory or aerobic fitness is a category of physical fitness that refers to the ability of circulatory and respiratory systems to supply skeletal muscles with the oxygen for energy generation during physical activity (Raghuveer et al., 2020). The role of physical exercise on impulsivity and cognitive control is primarily researched in connection with ADHD. For example, cardiorespiratory fitness was associated positively with attentional control in preadolescent children (Brassell et al., 2017) and negatively with impulsivity scores in male college students (Jeoung, 2014). The causal link between daily physical exercise and reduced impulsivity was also shown in several pilot studies (Smith et al., 2013; Choi et al., 2015). Whether a strong cardiorespiratory fitness prevents the expression of dysfunctional impulsivity in adults remains an open question; however, following a repetitive physical exercise regimen seems antithetical to impulsive actions.

During literature research, we found that most of the identified studies were cross-sectional in design and conducted on small samples, frequently on university students or children. Food habits and preferences were usually assessed by some type of survey rather than asking participants to keep diaries of the actual daily food intake. We identified 1 representative longitudinal cohort study that was part of the French NutriNet-Santé project conducted on a large sample of adult volunteers (Bénard et al., 2019). Dietary records in NutriNet-Santé study were collected every year; however, impulsivity was measured only once in older participants (average age 50 years), and micronutrient levels were not calculated from the dietary records.

Aims of the Study

We aimed to ascertain a possible longitudinal association between adaptive and maladaptive impulsivity dimensions and dietary intake. We expected that such associations would not be strong, but possible, as certain types of eating disorders and food choices have been previously associated with impulsivity. In particular, based on previous research, we expected that high maladaptive impulsivity would be associated with increased BMI and reduced cardiorespiratory fitness because the latter was predictive of symptoms of attention-deficit hyperactivity disorder at a young age in this sample (Muntaner-Mas et al., 2021). A primary role of many vitamins and metal ions is to serve as cofactors in neurotransmitter synthesis or ion channel gating, respectively, with implications particularly to both fast inhibitory and excitatory neurotransmission. Therefore, given a large sample size, we expected to find several associations with impulsivity. Because any associations between food choice and impulsivity could be bidirectional and the nutrients were calculated from the complete meals, the more parsimonious approach was to predict each impulsivity dimension in turn from the nutrients. To our knowledge, our study is the first to have such detailed nutrient categories, especially micronutrients, being longitudinal in design and simultaneously controlling for the other impulsivity dimension and fitness covariates.

METHODS AND MATERIALS

Participants and Data

Study Design and Participants—The sample included 2 birth cohorts of the longitudinal Estonian Children Personality, Behavior, and Health Study. The rationale and procedure for the original sample formation have been described in detail elsewhere (Harro et al., 2001). In brief, all schools of Tartu County, Estonia, that agreed to participate (54 of the total of 56) were included in the sampling, and 25 schools were selected to sample at least 1000 participants in total. All children from grades 3 (younger birth cohort, aged 9 years) and grades 9 (older birth cohort, aged 15 years) were invited to participate. Follow-up studies included in this paper took place in 3 waves at ages: 15 years (n = 483), 18 years (n = 454), and 25 years (n = 440) for the younger birth cohort and at ages 18 years (n = 461), 25 years (n = 541), and 33 years (n = 504) for the older birth cohort. The first proper impulsivity data were collected in the year 2001 for the older and 2004 for the younger cohort. Data were collected during a laboratory visit unless indicated otherwise. Written informed consent was obtained from the participants and from their parents if the participants were minors. The study was approved by the Ethics Review Committee on Human Research of the University of Tartu (license nos. 49/30, 151/11, 197T-14, and 235/M–20) and was conducted in accordance with the Declaration of Helsinki.

Impulsivity—Impulsivity was self-reported by filling out the AMIS questionnaire (Paaver et al., 2006). AMIS is a Likert-type questionnaire comprised of 24 five-choice items developed based on Dickman's concept of functional and dysfunctional impulsivity (Dickman, 1990). The example items for the maladaptive subscale are "I often immediately blurt out the first thing on my mind" and "Sometimes I cannot control my appetite." The example items for the adaptive subscale are "I like to be where the action is" and "I can make quick decisions even in unexpected situations." Response choice frequencies for AMIS items are provided in supplementary Figures 3 and 4. The full AMIS questionnaire and its scoring key are provided in supplementary Table 2.

Dietary Intake—The participants were asked to complete 48-hour (years 2001, 2004, and 2007) or 72-hour (years 2008 and 2014) food diaries at home during the days before the study day. On the study day, a face-to-face interview, using pictures of portion sizes (Haapa et al., 1985), was conducted to validate the information in the food diary as well as to specify intake that was not recorded. Food intake over several days was averaged to calculate the daily food intake. This food intake was then converted into composing micro- and macronutrients according to 2 reference sources of food composition: the Finnish Micro-Nutrica Nutritional Analysis program (Estonian version 2.0, Tallinn University of Technology, Food Processing Institute, Estonia) and the Estonian NutriData food consumption database (versions 4.0–7.0, National Institute for Health Development, Estonia) (Joost et al., 2019). The following macro- and micronutrients were included in the study: carbohydrates, lipids, proteins, meat, fish, eggs, dairy, cereal products, sugar and sweets, vegetables, fruits and berries, pure alcohol (all in grams per day); vitamins B1, B2, B3 (niacin), B6, C, E; calcium, iron, magnesium, manganese, phosphorus, potassium, sodium, zinc (all in milligrams per day); vitamins A (retinol), B12, D; folate, iodine, selenium (all in micrograms per day). Overall daily energy intake in kilocalories per day was also calculated.

Other Covariates—BMI was calculated as weight/height squared (kg/m^2). Cardiorespiratory fitness was determined using a cycle-ergometer (Tunturi T8, Tunturi New Fitness B.V., Finland) test with progressively increasing workload until exhaustion and was defined as maximal power output calculated per kilogram of body weight (MPO/kg bwt). In males, the initial workload was set at 50 W and increased by 50 W every 3 minutes until exhaustion. The respective workload parameters were set to 40 W in females. Criteria for exhaustion were a heart rate >185 bpm, failure to maintain pedaling frequency of at least 30 rpm, or a subjective judgment by the experimenter that the individual could no longer continue, even after encouragement (see Lätt et al., 2018 for more details). Venous blood samples (4.5 mL) were obtained after a fast of 8–12 hours by antecubital venipuncture into vacuum tubes (Vacutainer) containing 0.054 mL K3 Ethylenediaminetetraacetic acid (EDTA) as an anticoagulant. The samples were immediately centrifugated for 10 minutes, with 800 rpm, at room temperature obtaining platelet-rich plasma. Blood samples were then analyzed in a certified clinical laboratory. Insulin resistance was estimated using the homeostatic model assessment index, which was calculated as fasting glucose (mmol/l) × fasting insulin (mU/L)/22.5 (Matthews et al., 1985). Cholesterol, High-density lipoprotein (HDL) cholesterol, and Low-density lipoprotein (LDL) cholesterol were measured in mmol per liter except for the year 1998, where Low-density lipoprotein cholesterol was not measured but calculated based on the Friedewald formula (Winocour et al., 1989). Distributions of dietary and physiological variables used in the study are given in supplementary Figures 1 and 2. Supplementary Table 1 provides a descriptive summary of these variables stratified by age.

Outline of Data Analysis—The main steps of data analysis are depicted in Figure 1. Data validation and multiple imputation of missing data were followed by 2 streams of analysis. The main goal of the analysis was to find the best-fitting linear mixed models exploring associations of nutritional and physiological variables with 2 types of impulsivities. The secondary stream analyzed the psychometric performance of AMIS questionnaire and concluded with calculation of the latent impulsivity scores, which in turn were used to test the sensitivity of the best-fitting linear mixed models to a different method of calculating impulsivity scores.

Data Preprocessing—There were 2 main types of data missingness: all data for a survey wave were missing (attrition), or some indicators had missing data within a successful data collection wave. Additionally, in the older cohort at age 18, there were 3 missing items from the impulsivity questionnaire for all participants (items 6, 20, and 22) because AMIS was not fully developed at the time. We used multiple imputation of the missing data within successful data collection waves because it is the best way to produce unbiased statistical estimates (Figure 1). Imputation of the missing data also preserves the same number of observations, which allows the comparison of model fit scores between statistical models with different covariate structures. The missingness on different indicators varied between 0.58% and 33%. A multiple imputation of 100 plausible values was performed separately for each cohort in *Blimp* software (ver. 2.2) using the method of chained equations (Enders et al., 2018). AMIS items and dietary intake indicators were imputed in independent blocks, where age, sex, daily energy intake, cardiorespiratory fitness, and BMI were used as shared covariates between the 2 blocks.

The nominal rather than biological age of each survey wave (possible values 15, 18, 25, and 33 years) was used in statistical modeling to simplify the interpretation and visualization of the results. The age was centered at 18 years to join the data from 2 cohorts along the same time scale. All measures except for age and sex were standardized to Z-scores within each cohort and then merged. Sex was deviation coded so that the main effects in regression models would be sex neutral.

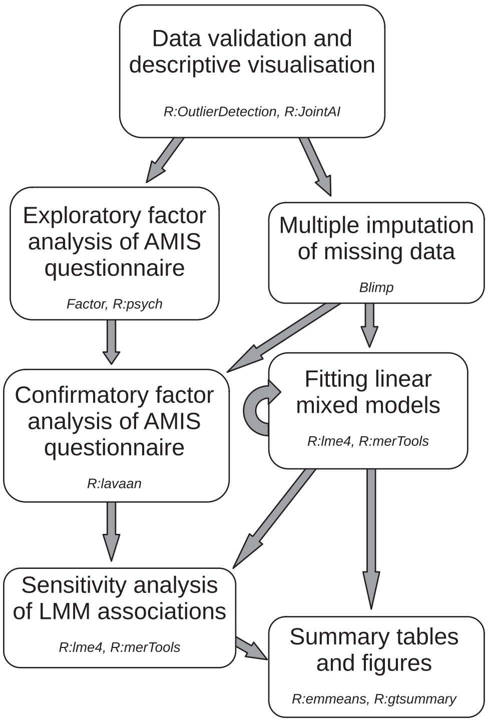

Figure 1. Flowchart of data analysis. Arrows indicate the direction of data analytic steps. Main computer software packages used to perform each analytic step are written in italic. R packages are prefixed with “R:”.

Statistical Analysis

Factor Analysis of AMIS Questionnaire—The analysis started with the psychometric re-validation of the AMIS questionnaire in this longitudinal, birth cohort representative sample. Factor analysis of AMIS items was performed on a polychoric correlation matrix using *Factor* software (Universitat Rovira i Virgili, Spain) (Lorenzo-Seva and Van Ginkel, 2016). The optimal number of common factors in the questionnaire was selected by the Hull method (Lorenzo-Seva et al., 2011). Robust diagonally weighted least-squares estimation with oblique promin rotation was used to fit the data. Missing values were imputed by a hot deck multiple imputation method offered by the *Factor* software. Factor loadings for the best-fitting 2-factor solution are provided in supplementary Table 3. Because the eighth item showed only weak loadings on either factor, it was excluded from the computation of the composite scores.

Latent Scores—A 2-factor exploratory factor analysis (EFA) was performed in *R* (R Core Team, 2022) with `fa` command from the *psych* package (Revelle, 2022) using weighted least-squares estimation and oblique rotation method *geominQ*. Following EFA, a model for the confirmatory factor analysis (CFA) was specified. For each factor (representing adaptive and maladaptive impulsivity), the loading magnitude was fixed for 1 item with the highest loading on that factor in EFA. Other factor loadings were freely estimated, and factor cross-loadings were permitted. This approach allowed to fit a flexible model appropriate for longitudinal data while preserving the same structure between fits on different imputed datasets. CFA was performed with *lavaan* package (Rosseel, 2012) using a diagonally weighted least-squares estimator and robust standard errors. Estimated subject scores on the 2 latent factors were computed using the Empirical Bayes Modal approach and used as substitutes for composite sum scores in regression analysis.

Linear Mixed Effects Models—Longitudinal measures of impulsivity, dietary intake, and physiological covariates were clustered within individuals; therefore, these data were modeled by a linear mixed effects approach (LMM) in *R* to account for the correlations between repeated measurements within a participant. Each individual was represented by a random intercept and, additionally, by a random age-dependent slope in some of the models. Unstructured variance-covariance matrix was specified for random effects. The maximum likelihood method was used to find the best-fitting model, whereas final model parameters were estimated by the restricted maximum likelihood. Models were fitted with the *lme4* package (Bates et al., 2015), which was extended for analysis of multiply imputed data with *merTools* package (Knowles and Frederick, 2020).

We modeled adaptive and maladaptive impulsivity scores separately and used 3 approaches to model fitting. Initially, the composite adaptive and maladaptive impulsivity scores were modeled in turn by including all nutrients and other covariates from which the best-fitting models were identified. The covariates with the weakest contribution to the model were removed in succession, while the model's fit was measured by the Akaike information criterion. The final model for each type of impulsivity had the lowest Akaike information criterion score and was adjusted for all significant covariates. Such an approach was preferred to the fully saturated model, as the number of covariates was rather large and the dietary intake data were inherently collinear. The fixed effects that defined each best-fitting model are provided in the left column of Tables 2 and 3. Additionally, sensitivity analyses were performed to test the strength of found associations against different model specifications.

Two more model types were tried: (1) the association between each dietary/physiological covariate and impulsivity was tested without the conditional adjustment on other covariates except for age and sex in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology guidelines (Elm et al., 2007); and (2) the best-fitting models were refitted with the same covariates, but composite impulsivity scores were substituted with the respective latent factor scores. Conceptually, a latent factor score is a score that would have been observed for a person if it had been possible to directly measure the factor. Latent factor scores weigh each item proportionally according to its loading on a common factor and therefore naturally assign low weights to items with little contribution to the latent factor.

All models were fit on 100 multiply imputed datasets. Parameter estimates from each imputed dataset were combined using Rubin's rules. Finally, the power analysis of fixed regression coefficients from the best-fitting LMMs was conducted with *simr* package (Green and MacLeod, 2016) using the parametric bootstrap test with 1000 simulations.

RESULTS

The Impulsivity Construct

Good psychometric properties of AMIS were confirmed by EFA. A 2-factor solution was the best fitting, and all items except the eighth showed significant loadings on their structural factor (supplementary Table 2). The eighth item was only weakly associated with either of the latent factors and therefore was excluded from the calculation of composite scores. The psychometric properties of AMIS were good: standardized Cronbach's alpha = .85, generalized H construct reliability indices were 0.91 (95% CI = 0.897 to 0.913) for maladaptive and 0.90 (95% CI = 0.894 to 0.908) for adaptive impulsivity factors, respectively. The 2 common factors accounted for 64.4% of the observed variance among AMIS items.

Besides the unweighted composite impulsivity scores, the exploratory CFA approach was used to compute latent factor scores that weigh each item's contribution according to its

Table 1. Descriptive Summary of the Variables Used in the Best Fitting Linear Mixed Effects Conditioned on Age

Variable	15 y, n = 483[a]	18 y, n = 915[a]	25 y, n = 981[a]	33 y, n = 504[a]	P value[b]
Sex					.63
Female	261 (54%)	515 (56%)	556 (57%)	293 (58%)	
Male	222 (46%)	400 (44%)	425 (43%)	211 (42%)	
Age, y	15.3 (15.0–15.6)	18.3 (17.9–18.7)	25.3 (24.9–25.6)	33.5 (33.1–33.9)	<.001
Adaptive impulsivity scale, units	41 (36–46)	41 (35–46)	39 (34–44)	37 (31–43)	<.001
Missing	3	462	43	2	
Maladaptive impulsivity scale, units	34 (29–38)	33 (27–38)	30 (25–35)	28 (24–34)	<.001
Missing	3	462	43	2	
Maximum power output, per kg bwt	2.69 (2.27–3.32)	2.39 (2.03–2.99)	2.62 (2.16–3.15)	2.43 (2.09–2.98)	<.001
Missing	4	84	97	57	
Pure alcohol, g	0 (0–0)	0 (0–0)	0 (0–7)	0 (0–6)	<.001
Missing	5	33	43	17	
Vegetables, g	71 (38–115)	91 (47–150)	107 (60–173)	118 (72–184)	<.001
Missing	5	33	43	17	
Cereal products, g	205 (132–286)	212 (139–324)	150 (101–220)	121 (82–164)	<.001
Missing	5	33	43	17	
Fish, g	0 (0–0)	0 (0–0)	0 (0–36)	0 (0–42)	<.001
Missing	5	33	43	17	
Sodium, mg	2448 (1812–3467)	2696 (1971–3801)	2085 (1500–2968)	2066 (1464–2954)	<.001
Missing	5	33	43	17	
Zinc, mg	9.4 (7.0–12.4)	7.4 (4.1–11.4)	9.4 (7.4–12.4)	10.4 (7.9–15.1)	<.001
Missing	5	33	43	17	
Selenium, µg	61 (44–81)	66 (49–93)	56 (42–74)	57 (42–77)	<.001
Missing	5	33	43	17	
Vitamin B6, mg	1.50 (1.12–2.08)	1.53 (1.13–2.11)	1.30 (1.00–1.80)	1.30 (1.00–1.80)	<.001
Missing	5	33	43	17	

A similar summary for all variables used in the study is provided in supplementary Table 1.

[a] Statistics presented: n (%) for categorical variables; median (interquartile range) for numerical variables.

[b] Statistical tests performed: chi-square test of independence for categorical variables; Kruskal-Wallis rank-sum test for continuous variables

Table 2. Predictors of Maladaptive Impulsivity: Estimated Standardized Regression Coefficients and Their 95% Cis for Maladaptive Impulsivity Score as the Outcome Variable

	Unweighted composite scores: best fitting model	Unweighted composite scores: models adjusted for sex and age[a]	Latent factor scores: adjusted model[b]
Age centered at 18 y	−0.029***	−0.042***	−0.025***
	(−0.035; −0.023)	(−0.047; −0.037)	(−0.031; −0.020)
Sex: (female—male)	0.169**	0.160**	0.181***
	(0.053; 0.285)	(0.065; 0.256)	(0.075; 0.287)
Adaptive impulsivity score	0.162***	0.160***	−0.135***
	(0.123; 0.201)	(0.121; 0.199)	(−0.181; −0.089)
Maximum power output	−0.072**	−0.078***	−0.057**
	(−0.116; −0.028)	(−0.123; −0.034)	(−0.097; −0.017)
Zinc	−0.103***	−0.042*	−0.094***
	(−0.148; −0.059)	(−0.078; −0.006)	(−0.134; −0.053)
Selenium	0.066**	0.016	0.050*
	(0.018; 0.114)	(−0.020; 0.051)	(0.006; 0.094)
Sodium	0.060**	0.035	0.056**
	(0.016; 0.104)	(−0.001; 0.071)	(0.016; 0.096)
Fish	−0.047**	−0.029	−0.042**
	(−0.080; −0.014)	(−0.061; 0.003)	(−0.072; −0.012)
Vegetables	−0.039*	−0.036*	−0.039**
	(−0.072; −0.007)	(−0.068; −0.004)	(−0.068; −0.010)
Alcohol	0.036*	0.039*	0.014
	(0.004; 0.067)	(0.007; 0.071)	(−0.015; 0.043)
Sodium × sex: (female—male)	0.091**	0.102**	0.077*
	(0.023; 0.160)	(0.032; 0.172)	(0.014; 0.141)
n	2883	2883	2883

Abbreviation: CI, confidence interval.

***P < .001; **P < .01; *P < .05. Regression coefficients are standardized. 95% CIs are given in parentheses.

[a] These models included sex, age, and the variable in the respective row.

[b] The model includes the same variables as the best-fitting model on the left.

Table 3. Predictors of Adaptive Impulsivity: Estimated Standardized Regression Coefficients and Their 95% CIs for Adaptive Impulsivity Score as the Outcome Variable

	Unweighted composite scores: best-fitting model	Unweighted composite scores: models adjusted for sex and age[a]	Latent factor scores: adjusted model[b]
Age centered at 18 y	−0.021***	−0.023***	−0.036***
	(−0.027; −0.015)	(−0.028; −0.018)	(−0.041; −0.031)
Sex: (female—male)	−0.368***	−0.367***	−0.203***
	(−0.473; −0.262)	(−0.469; −0.265)	(−0.303; −0.104)
Maladaptive impulsivity score	0.148***	0.146***	−0.115***
	(0.113; 0.184)	(0.110; 0.182)	(−0.157; −0.072)
Zinc	0.042*	0.035*	0.008
	(0.002; 0.081)	(0.001; 0.068)	(−0.028; 0.044)
Vitamin B6	0.039*	0.048**	0.037*
	(0.006; 0.073)	(0.016; 0.080)	(0.006; 0.068)
Cereal products	−0.041*	−0.020	−0.026
	(−0.076; −0.005)	(−0.053; 0.013)	(−0.060; 0.007)
Age × sex: (female—male)	−0.013**	−0.016***	−0.013**
	(−0.023; −0.003)	(−0.026; −0.007)	(−0.021; −0.004)
n	2883	2883	2883

Abbreviation: CI, confidence interval.

***P < .001; **P < .01; *P < .05; Regression coefficients are standardized. 95% CI are given in parentheses.

[a] These models included sex, age, and the variable in the respective row.

[b] The model includes the same variables as the best-fitting model on the left.

loadings on the common factor. The CFA model fit was acceptable: the standardized root mean square residual was 0.073 (95% CI = 0.072 to 0.075), the comparative fit index was 0.93 (0.927 to 0.932), and the robust comparative fit index was 0.77 (0.76 to 0.78).

Predictors of Impulsivity

Descriptive summaries of the variables used as predictors of impulsivity are presented in Table 1, and the conditional associations between maladaptive impulsivity scores with covariates

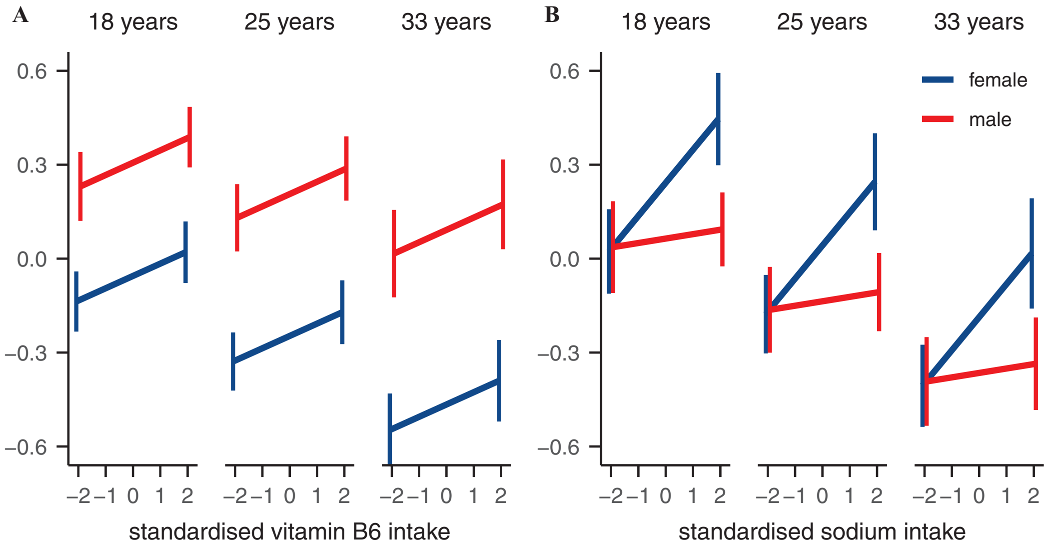

Figure 2. Predicted associations between vitamin B6, sodium, and impulsivity. Estimated standardized marginal means from the best fitting LMMs. Association between vitamin B6 and standardized adaptive impulsivity score (y-axis) conditioned on sex and age (A). Association between sodium and standardized maladaptive impulsivity score (y-axis) conditioned on sex and age (Panel B).

are provided in Table 2. The marginal coefficient of determination (R^2) for the best-fitting model was 0.11, while the conditional R^2 was 0.59. The marginal R^2 relays only the variance of the fixed effects, while the conditional R^2 accounts for both the fixed and random effects (Nakagawa et al., 2017). In the full model with latent factor scores, the respective parameters were 0.09 and 0.54. All models agreed that maladaptive impulsivity declined with age and was higher in females. Regardless of the sex, higher maladaptive impulsivity was associated with lower dietary intake of zinc, vegetables, and cardiorespiratory fitness. In contrast, the association of sodium intake with maladaptive impulsivity was stronger among females. Adjusted models additionally indicated a positive association of maladaptive impulsivity with selenium intake and a negative association between maladaptive impulsivity and fish consumption. A positive association between maladaptive impulsivity and alcohol consumption was statistically weak, and it disappeared in the model with latent factor scores.

The conditional associations between adaptive impulsivity scores with covariates are given in Table 3. The marginal R^2 for the main model was 0.10, while the conditional R^2 was 0.65. In the full model with latent factor scores, the respective parameters were 0.10 and 0.59. All models demonstrated that adaptive impulsivity declined with age and was higher in males. The age-dependent decline was steeper among females. Adaptive impulsivity was associated with fewer covariates compared with maladaptive impulsivity. All models showed a positive association of vitamin B6 intake with adaptive impulsivity. Zinc intake was also positively associated with adaptive impulsivity, but this effect disappeared in the model with latent factor scores.

Both factor analysis and LMM approaches showed that 2 impulsivity scales share some common variance as adaptive and maladaptive impulsivity scores were positively correlated. However, the latent factor scores approach to modeling reduced the magnitude of correlation between the 2 dimensions of impulsivity. Diagnostic plots of the best-fitting LMMs are provided in supplementary Figure 5. The marginal best-fitting model estimates of the associations between sodium and maladaptive impulsivity, as well as vitamin B6 and adaptive impulsivity, are illustrated in Figure 2.

As an additional check on our results, we conducted a simulation to estimate the statistical power of our best-fitting models to reject the null hypothesis. If we take the conventional benchmark for statistical power to reject the null hypothesis of 80%, then in the maladaptive impulsivity model the results for alcohol of 73.8% (95% CI = 69.7% to 77.6%) and vegetables of 75% (71% to 78.7%) were underpowered. The results for other covariates were appropriately powered. For example, for cardiorespiratory fitness, the power was 92.2% (89.5% to 94.4%) and for adaptive impulsivity, age, and zinc the power was 100% (99.3% to 100%). The predictors in the adaptive impulsivity LMM were less well powered: zinc had the highest *P* value, and this result was underpowered at 47.2% (42.8% to 51.7%). The vitamin B6 result was also underpowered at 61.6% (57.2% to 65.9%). For cereal products, the power was 62.8% (58.4% to 67.1%). The power for the interaction between age and sex was 78.2% (74.3% to 81.7%). Age, adaptive impulsivity, and sex were well-powered at 100% (99.3% to 100%).

Discussion

In the current study, the domain of impulsivity was divided into functional and dysfunctional impulsivity. It is not the most popular approach to study impulsivity, because most studies concentrate on dysfunctional impulsivity, especially in clinical settings. However, our goal was to measure everyday manifestations of impulsivity rather than concentrate on clinical pathology. Such an approach is rooted in the understanding that impulsivity is a multifaceted phenomenon that spans the continuum from calculated risk-taking and adventurousness to pathological, harmful to the subject manifestations of impulsiveness (Evenden, 1999; Whiteside and Lynam, 2001; Strickland and Johnson, 2021). First, we re-validated the impulsivity questionnaire (AMIS) on the longitudinal sample. A brief history of the AMIS is required here to explain its relationship to Dickman's concepts of functional and dysfunctional impulsivity. In the process of adaptation of the

Estonian version of Dickman's scale, it was found that the items from the functional impulsivity subscale loaded on the same factor as personality Revised NEO Personality Inventory (NEO-PI-R) (Costa and McCrae, 2008). Extraversion scale items and the items of dysfunctional impulsivity subscale loaded on the same factor as NEO-PI-R Neuroticism scale items (Pulver, A., unpublished data). Based on factor structure, items from the Estonian NEO-PI-R items pool were added to Dickman's subscales. Conceptually, impulsivity is a manifestation of cognitive, emotional, and behavioral aspects of personality traits (Whiteside and Lynam, 2001; Fischer et al., 2008), and it is reasonable to extend Dickman's functional and dysfunctional impulsivity concept to a more dispositional personality construct. Because AMIS combines items from the original Dickman's impulsivity scale with NEO-PI-R items, the 2 primary dimensions of the questionnaire were named adaptive and maladaptive impulsivity to avoid confusion. Previously, AMIS scores were used to investigate driving and substance abuse: adaptive and maladaptive impulsivity scores were associated with risky driving and alcohol abuse in nationally representative samples of car drivers (Eensoo et al., 2004; Paaver et al., 2006; Luht et al., 2019) and in a cross-sectional analysis on the ECPBHS (Laas et al., 2010).

Both dimensions of impulsivity declined with age and showed sex dependence: adaptive impulsivity scores were higher among males, and maladaptive impulsivity scores were higher among females. AMIS impulsivity scales were conditionally correlated with a magnitude of approximately 0.2, which agrees well with the magnitude (0.23) of correlation between functional and dysfunctional scales reported by Dickman (1990) and other authors (Chico et al., 2003; Miller et al., 2004). Maladaptive impulsivity was slightly better explained by the included covariates than adaptive impulsivity, because marginal R^2 coefficients were 0.11 and 0.10 for the respective best-fitting models. Inclusion of the individual-specific variance in LMMs was well justified, because conditional R^2 coefficients indicated that best-fitting models accounted for over 50% of the total variance. These results show that, as expected, nutritional and selected physiological data can account for only approximately 10% of impulsivity-related variance. Many other variables with potential explanatory power, such as genetic variants or environmental factors of other types, were not included in the present analysis. However, due to their relative stability, these unaccounted variables manifested themselves via high individual-specific variance, as shown by conditional R^2.

All 3 modeling approaches indicated a negative relationship between maladaptive impulsivity and cardiorespiratory fitness, the intake of zinc and vegetables, and positive association with sodium intake in females. Vitamin B6 intake was positively associated with adaptive impulsivity. To our knowledge, the current study of the associations between impulsivity and dietary intake is the first extensive, longitudinal investigation with 2 waves of follow-up and a nationally representative sample. Therefore, obtaining similar results with the composite sum of item scores and latent factor scores approaches provides a good confidence boost to the overall validity of the associations.

We found that associations between impulsivity and dietary intake were more numerous and potent for the maladaptive scale, measuring a more personally harmful dimension of impulsivity. Among the nutrients, zinc intake was associated with both dimensions of impulsivity in the best-fitting models of composite scores (negatively with maladaptive and positively with adaptive impulsivity), while selenium intake was positively associated with maladaptive impulsivity in adjusted models. However, association of zinc with adaptive impulsivity was weaker and did not persist in the latent factor scores model. Adjusted models also showed a significantly reduced fish intake and higher alcohol consumption in individuals with high maladaptive impulsivity scores. Hence, these associations became significant only conditional on adjustment for other nutrients, probably because both food categories are not consumed every day, and the statistical relationship was supported by fewer observations. The direction of association with alcohol consumption is well supported in the literature (Dick et al., 2010). Fish is the primary source of essential fatty acids. Dietary supplementation with essential fatty acids is advocated as a treatment of ADHD and hostile behavior (Garland and Hallahan, 2006). Overall, the pattern of associations between macronutrients and maladaptive impulsivity agrees with common sense and the results from a recent French NutriNet-Santé study (Bénard et al., 2019). In contrast to maladaptive impulsivity, the model of adaptive impulsivity showed fewer, statistically weaker associations with nutrients. The only positive association that all 3 modeling approaches agreed on was with vitamin B6. This possibly means that the adaptive impulsivity dimension is less related to specific, especially unhealthy, eating habits.

A notable non-association was BMI. The association between impulsivity and BMI in the literature appears to be relatively weak and scale dependent (Meule and Platte, 2015; Emery and Levine, 2017). Most participants in our study were of normal weight, which likely reduced the range of the possible association between impulsivity and BMI. Such association is likely more pronounced on the right tail for both dimensions. Of the significant associations, we would like to highlight the strong association between lower dietary zinc intake and higher maladaptive impulsivity scores. Zinc is an essential trace mineral vital for neurotransmitter synthesis (Robberecht et al., 2020). Vesicular zinc is released into the synaptic cleft coincidentally with glutamate and acts as a modulator of glutamatergic neurotransmission, primarily via inhibition of N-methyl-D-aspartate (NMDA) receptors (McAllister and Dyck, 2017). Low zinc levels have been studied as a potential causative factor in ADHD symptomatology. The current consensus seems to be, however, that a Western diet provides adequate levels of dietary zinc, and additional zinc supplementation beyond cases of substantial zinc deficiency does not protect against ADHD (Arnold et al., 2011; Robberecht et al., 2020). Impulsivity is the core component of ADHD, and the possible role of zinc in the genesis of impulsivity requires further research. Additionally, low dietary zinc intake and genetic dysregulation of zinc homeostasis are linked to metabolic abnormalities and diabetes (Fukunaka and Fujitani, 2018). Similarly to zinc, vitamin B6 is also an essential co-factor in many enzymatic reactions (Stover and Field, 2015), and its association with adaptive impulsivity suggests that vitamin B6 affects decision-making. Interestingly, a positive association between schizophrenia polygenic score and vitamin B6 intake was found in UK Biobank data (Hunjan et al., 2021).

Cardiorespiratory fitness exhibited a negative association with maladaptive impulsivity. As mentioned above, several studies in children have been dedicated to studying impulsivity indirectly via its inclusion in the definition of ADHD. Besides the studies mentioned in the introduction, a previous study of the ECPBHS participants indicated that being unfit in childhood (at age 9) increases the likelihood of exhibiting ADHD symptoms 6 years later in adolescence, adjusted for baseline ADHD symptoms and BMI (Muntaner-Mas et al., 2021). Nevertheless, dedicated studies, especially on the non-clinical adult samples, remain scarce. In the few identified studies, cardiorespiratory fitness was positively associated with performance on several cognitive tasks in young adult women (Scott et al., 2016) and lower interference in the Stroop test in young adult men (Ludyga et al., 2019). A sex-linked positive association in males only was found between the higher cardiorespiratory fitness and the performance in sustained attention tasks (Wade et al., 2020). A recent study on German adults found that all 3 subscales of the Three-Factor Impulsivity scale were negatively correlated with the duration of weekly physical exercise (Javelle et al., 2021b). However, the current longitudinal study is the first to our knowledge to report the negative association between trait impulsivity and fitness levels that persists throughout adolescence and young adulthood.

Impulsivity is widely used as a diagnostic criterion in clinical practice and to describe various forms of suboptimal decision making. It has been even claimed that "after subjective distress, impulsivity may be the most common diagnostic criteria in the fourth version of the Diagnostic and Statistical Manual for Mental Disorders" (Whiteside and Lynam, 2001). Such ubiquity of impulsivity in psychopathology requires a more critical look at the concept of impulsivity itself and its measurement, because we are very likely dealing with a multidimensional concept. For example, the best-known modern scale of impulsivity (Urgency, Premeditation, Perseverance, Sensation Seeking Impulsive Behaviour Scale) divides impulsivity into at least 4 dimensions: urgency, (lack of) premeditation, (lack of) perseverance, and sensation-seeking (Whiteside and Lynam, 2001; Rochat et al., 2018). We used a more straightforward approach of dividing impulsivity into adaptive and maladaptive scales, which, probably, does not fully represent the interplay between impulsivity dimensions and diet. However, the specificity of higher alcohol and lower fish/vegetable intake associations with the more harmful dimension of maladaptive impulsivity agrees well with the existing clinical and observational knowledge. Such observations give us confidence that novel associations obtained with zinc and vitamin B6 are also relevant in explaining the genesis of impulsive behavior. This assertion may seem counter-intuitive, because it would be more natural to assume that the impulsive disposition leads to certain nutritional outcomes; however, causal inference in nutritional epidemiology is difficult (Ohukainen et al., 2022). For example, based on data from genome-wide association studies, it was shown that ADHD symptoms and loneliness are among phenotypes related to obesity (García-Marín et al., 2021). Our results show a possible feedback loop: food preferences may affect neurochemistry and therefore regulate the frequency of impulsive actions and thoughts. Micronutrients such as minerals and vitamins are essential factors in metabolic pathways, and their levels should be assessed more widely in studies of mental health and nutrition.

Our study has several limitations. It was purely observational and did not measure the physiological concentrations of micronutrients. The estimation of nutrients from the observational data is imprecise and is affected by longitudinal changes in the measurement instruments, dietary habits, and food technology (Vaask et al., 2004). Only few studies have researched the validity of measuring the dietary intake from food diaries against a direct observation (Karvetti and Knuts, 1992; Gariballa and Forster, 2008). Both studies agreed that food diaries provide a valid method of measuring dietary intake across ages. The participants' food intake was measured for only a few days, and there were gaps of 3 to 8 years between subsequent study waves. Between follow-up studies, Estonian society was changing rapidly, including in its dietary behavior: BMI and obesity rates increased over the period of 2006–2018 (Reile et al., 2020). The association of adaptive impulsivity with the predictors used in our models was relatively weak, and the effect sizes were statistically underpowered. On the other hand, a psychometrically sound instrument was used to measure both dimensions of impulsivity, and the best predictors of maladaptive impulsivity were adequately powered. It is also the first study on the representative national sample that concurrently tracks the longitudinal association between impulsivity and dietary intake. Several biobanks in European countries have been collecting dietary records, but most of them do not collect a battery of psychometrically validated scales to measure different psychological constructs. The Estonian population is quite homogeneous genetically, and its dietary habits have changed in the last 30 years, which suggests that these results may not generalize well to other populations. The study is ongoing, and further updates on the topic are forthcoming. Because elevated impulsivity is characteristic of several psychiatric disorders, our study may have some clinical relevance. Zinc can be provided as an adjunct treatment to psychiatric patients with symptoms of impulsivity and poor self-control. Although to date there is no clear evidence of the utility of such treatment, there nevertheless might exist a small positive effect on treatment outcomes, and even the smallest clinical effects accumulate over time and improve treatment prognosis.

The present report is the first longitudinal study, to our knowledge, of such breadth to investigate the associations between the 2 impulsivity dimensions of dietary intake and cardiorespiratory fitness. It confirmed the heterogeneous nature of impulsivity. The dimension of maladaptive impulsivity was reflected in dietary choices and fitness levels. Furthermore, the negative association of zinc intake with maladaptive impulsivity as well as positive association of vitamin B6 intake with adaptive impulsivity are novel findings.

Supplementary Materials

Supplementary data are available at *International Journal of Neuropsychopharmacology (IJNPPY)* online.

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Interest Statement: None.

Availability of Data and Materials

All data analysis scripts and results files are available for review. The analysis scripts are available in the Zenodo repository (https://zenodo.org/record/4543947). The data files are available upon reasonable request from the corresponding author.

References

Adams WK, Sussman JL, Kaur S, D'souza AM, Kieffer TJ, Winstanley CA (2015) Long-term, calorie-restricted intake of a high-fat diet in rats reduces impulse control and ventral striatal D_2 receptor signalling – two markers of addiction vulnerability. Eur J Neurosci 42:3095–3104.

Arnold LE, DiSilvestro RA, Bozzolo D, Bozzolo H, Crowl L, Fernandez S, Ramadan Y, Thompson S, Mo X, Abdel-Rasoul M, Joseph E (2011) Zinc for attention-deficit/hyperactivity disorder: placebo-controlled double-blind pilot trial alone and combined with amphetamine. J Child Adolesc Psychopharmacol 21:1–19.

Bates D, Mächler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67:1–48.

Bénard M, Bellisle F, Kesse-Guyot E, Julia C, Andreeva VA, Etilé F, Reach G, Dechelotte P, Tavolacci M-P, Hercberg S, Péneau S (2019) Impulsivity is associated with food intake, snacking, and eating disorders in a general population. Am J Clin Nutr 109:117–126.

Berg JM, Latzman RD, Bliwise NG, Lilienfeld SO (2015) Parsing the heterogeneity of impulsivity: a meta-analytic review of the behavioral implications of the UPPS for psychopathology. Psychol Assess 27:1129–1146.

Brassell AA, Shoulberg EK, Pontifex MB, Smith AL, Delli Paoli AG, Hoza B (2017) Aerobic fitness and inhibition in young children: moderating roles of ADHD status and age. J Clin Child Adolesc Psychol 46:646–652.

Chico E, Tous JM, Lorenzo-Seva U, Vigil-Colet A (2003) Spanish adaptation of Dickman's Impulsivity Inventory: its relationship to Eysenck's Personality Questionnaire. Pers Indiv Diff 35:1883–1892.

Choi JW, Han DH, Kang KD, Jung HY, Renshaw PF (2015) Aerobic exercise and attention deficit hyperactivity disorder: brain research. Med Sci Sports Exerc 47:33–39.

Costa PT, McCrae RR (2008) The Revised NEO Personality Inventory (NEO-PI-R). In: The SAGE handbook of personality theory and assessment, Vol. 2. Personality measurement and testing (Boyle GJ, Matthews G, Saklofske DH, eds), pp179–198. London: SAGE Publications.

Daruna JH, Barnes PA (1993) A neurodevelopmental view of impulsivity. In: The impulsive client: theory, research, and treatment (McCown WG, Johnson JL, Shure MB, eds), pp23–37. Washington, DC: American Psychological Association.

Dick DM, Smith G, Olausson P, Mitchell SH, Leeman RF, O'Malley SS, Sher K (2010) Understanding the construct of impulsivity and its relationship to alcohol use disorders. Addict Biol 15:217–226.

Dickman SJ (1990) Functional and dysfunctional impulsivity: personality and cognitive correlates. J Pers Soc Psychol 58:95–102.

Eensoo D, Paaver M, Pulver A, Harro M, Harro J (2004) Low platelet MAO activity associated with high dysfunctional impulsivity and antisocial behavior: evidence from drunk drivers. Psychopharmacology 172:356–358.

Elm E von, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP (2007) Strengthening the reporting of observational studies in epidemiology (STROBE) statement: guidelines for reporting observational studies. BMJ 335:806–808.

Emery RL, Levine MD (2017) Questionnaire and behavioral task measures of impulsivity are differentially associated with body mass index: a comprehensive meta-analysis. Psychol Bull 143:868–902.

Enders CK, Keller BT, Levy R (2018) A fully conditional specification approach to multilevel imputation of categorical and continuous variables. Psychol Methods 23:298–317.

Evenden JL (1999) Varieties of impulsivity. Psychopharmacology 146:348–361.

Eysenck SBG (2004) How the impulsiveness and venturesomeness factors evolved after the measurement of psychoticism. In: On the psychobiology of personality (Stelmack RM, ed), pp 107–112. Amsterdam: Elsevier.

Fischer S, Smith G, Cyders M (2008) Another look at impulsivity: a meta-analytic review comparing specific dispositions to rash action in their relationship to bulimic symptoms. Clin Psychol Rev 28:1413–1425.

Fleig L, Lippke S, Pomp S, Schwarzer R (2011) Intervention effects of exercise self-regulation on physical exercise and eating fruits and vegetables: a longitudinal study in orthopedic and cardiac rehabilitation. Prev Med 53:182–187.

Fukunaka A, Fujitani Y (2018) Role of zinc homeostasis in the pathogenesis of diabetes and obesity. Int J Mol Sci 19:476.

García-Marín LM, Campos AI, Kho P-F, Martin NG, Cuéllar-Partida G, Rentería ME (2021) Phenome-wide screening of GWAS data reveals the complex causal architecture of obesity. Hum Genet 140:1253–1265.

Gariballa SE, Forster SJ (2008) Dietary intake of older patients in hospital and at home: the validity of patient kept food diaries. J Nutr Health Aging 12:102–106.

Garland MR, Hallahan B (2006) Essential fatty acids and their role in conditions characterised by impulsivity. Int Rev Psychiatry 18:99–105.

Garman TS, Setlow B, Orsini CA (2021) Effects of a high-fat diet on impulsive choice in rats. Physiol Behav 229:113260.

Green P, MacLeod CJ (2016) simr: an R package for power analysis of generalised linear mixed models by simulation. Methods Ecol Evol 7:493–498.

Grudet C, Malm J, Westrin A, Brundin L (2014) Suicidal patients are deficient in vitamin D, associated with a pro-inflammatory status in the blood. Psychoneuroendocrinology 50:210–219.

Haapa E, Toponen T, Pietinen P, Räsänen L (1985) Annoskuvakirja (Picture book on food portions). Helsinki, Finland: Kansanterveyslaitos.

Harro M, Eensoo D, Kiive E, Merenäkk L, Alep J, Oreland L, Harro J (2001) Platelet monoamine oxidase in healthy 9- and 15-years old children: the effect of gender, smoking and puberty. Prog Neuropsychopharmacol Biol Psychiatry 25:1497–1511.

Hudson NW, Fraley RC (2015) Volitional personality trait change: can people choose to change their personality traits? J Pers Soc Psychol 109:490–507.

Hudson NW, Fraley RC, Chopik WJ, Briley DA (2020) Change goals robustly predict trait growth: a mega-analysis of a dozen intensive longitudinal studies examining volitional change. Soc Psychol Personal Sci 11:723–732.

Hunjan AK, Hübel C, Lin Y, Eley TC, Breen G (2021) Association between polygenic propensity for psychiatric disorders and nutrient intake. Commun Biol 4:965.

Jasinska AJ, Yasuda M, Burant CF, Gregor N, Khatri S, Sweet M, Falk EB (2012) Impulsivity and inhibitory control deficits are associated with unhealthy eating in young adults. Appetite 59:738–747.

Javelle F, Li D, Zimmer P, Johnson SL (2021a) Dietary intake of tryptophan tied emotion-related impulsivity in humans. Int J Vitam Nutr Res 91:69–76.

Javelle F, Wiegand M, Joormann J, Timpano KR, Zimmer P, Johnson SL (2021b) The German Three Factor Impulsivity Index: confirmatory factor analysis and ties to demographic and health-related variables. Personal Individ Differ 171:110470.

Jeoung BJ (2014) The relationship between attention deficit hyperactivity disorder and health-related physical fitness in university students. J Exerc Rehabil 10:367–371.

Joost U, Villa I, Comasco E, Oreland L, Veidebaum T, Harro J (2019) Association between Transcription Factor AP-2B genotype, obesity, insulin resistance and dietary intake in a longitudinal birth cohort study. Int J Obes 43:2095–2106.

Karvetti R-L, Knuts L-R (1992) Validity of the estimated food diary: comparison of 2-day recorded and observed food and nutrient intakes. J Am Diet Assoc 92:580–584.

Knowles JE, Frederick C (2020) merTools: tools for analyzing mixed effect regression models. https://CRAN.R-project.org/package=merTools. Accessed September 3, 2022.

Laas K, Reif A, Herterich S, Eensoo D, Lesch K-P, Harro J (2010) The effect of a functional NOS1 promoter polymorphism on impulsivity is moderated by platelet MAO activity. Psychopharmacology 209:255–261.

Lätt E, Jürimäe J, Harro J, Loit H-M, Mäestu J (2018) Low fitness is associated with metabolic risk independently of central adiposity in a cohort of 18-year-olds. Scand J Med Sci Sports 28:1084–1091.

Liu L, Artigas SO, Ulrich A, Tardu J, Mohr PNC, Wilms B, Koletzko B, Schmid SM, Park SQ (2021) Eating to dare – nutrition impacts human risky decision and related brain function. NeuroImage 233:117951.

Lorenzo-Seva U, Timmerman ME, Kiers HAL (2011) The Hull method for selecting the number of common factors. Multivar Behav Res 46:340–364.

Lorenzo-Seva U, Van Ginkel JR (2016) Multiple imputation of missing values in exploratory factor analysis of multidimensional scales: estimating latent trait scores. An Psicol 32:596.

Ludyga S, Mücke M, Colledge FMA, Pühse U, Gerber M (2019) A combined EEG-fNIRS study investigating mechanisms underlying the association between aerobic fitness and inhibitory control in young adults. Neuroscience 419:23–33.

Luht K, Tokko T, Eensoo D, Vaht M, Harro J (2019) Efficacy of intervention at traffic schools reducing impulsive action, and association with candidate gene variants. Acta Neuropsychiatr 31:159–166.

Lumley J, Stevenson RJ, Oaten MJ, Mahmut M, Yeomans MR (2016) Individual differences in impulsivity and their relationship to a Western-style diet. Personal Individ Differ 97:178–185.

Matthews DR, Hosker JP, Rudenski AS, Naylor BA, Treacher DF, Turner RC (1985) Homeostasis model assessment: insulin resistance and β-cell function from fasting plasma glucose and insulin concentrations in man. Diabetologia 28:412–419.

McAllister BB, Dyck RH (2017) Zinc transporter 3 (ZnT3) and vesicular zinc in central nervous system function. Neurosci Biobehav Rev 80:329–350.

Meule A, Platte P (2015) Facets of impulsivity interactively predict body fat and binge eating in young women. Appetite 87:352–357.

Miller E, Joseph S, Tudway J (2004) Assessing the component structure of four self-report measures of impulsivity. Personal Individ Differ 37:349–358.

Muntaner-Mas A, Ortega FB, Femia P, Kiive E, Eensoo D, Mäestu J, Franke B, Reif A, Faraone SV, Harro J (2021) Low cardiorespiratory fitness and obesity for ADHD in childhood and adolescence: a 6-year cohort study. Scand J Med Sci Sports 31:903–913.

Nakagawa S, Johnson PCD, Schielzeth H (2017) The coefficient of determination R^2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. J R Soc Interface 14:20170213.

Ohukainen P, Virtanen JK, Ala-Korpela M (2022) Vexed causal inferences in nutritional epidemiology—call for genetic help. Int J Epidemiol 51:6–15.

Paaver M, Eensoo D, Pulver A, Harro J (2006) Adaptive and maladaptive impulsivity, platelet monoamine oxidase (MAO) activity and risk-admitting in different types of risky drivers. Psychopharmacology 186:32–40.

R Core Team (2022) R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Available at: https://www.R-project.org/.

Raghuveer G, Hartz J, Lubans DR, Takken T, Wiltz JL, Mietus-Snyder M, Perak AM, Baker-Smith C, Pietris N, Edwards NM, On behalf of the American Heart Association Young Hearts Athero, Hypertension and Obesity in the Young Committee of the Council on Lifelong Congenital Heart Disease and Heart Health in the Young (2020) Cardiorespiratory fitness in youth: an important marker of health: a scientific statement from the American Heart Association. Circulation 142:e101–e118.

Reile R, Baburin A, Veideman T, Leinsalu M (2020) Long-term trends in the body mass index and obesity risk in Estonia: an age–period–cohort approach. Int J Public Health 65:859–869.

Revelle W (2022) psych: procedures for psychological, psychometric, and personality research. Evanston, Illinois: Northwestern University. Available at: https://CRAN.R-project.org/package=psych.

Robberecht H, Verlaet AAJ, Breynaert A, De Bruyne T, Hermans N (2020) Magnesium, iron, zinc, copper and selenium status in attention-deficit/hyperactivity disorder (ADHD). Molecules 25:4440.

Rochat L, Billieux J, Gagnon J, Van der Linden M (2018) A multifactorial and integrative approach to impulsivity in neuropsychology: insights from the UPPS model of impulsivity. J Clin Exp Neuropsychol 40:45–61.

Rosseel Y (2012) lavaan: an R package for structural equation modeling. J Stat Softw 48:1–36.

Sanchez-Roige S, Fontanillas P, Elson SL, Gray JC, de Wit H, MacKillop J, Palmer AA (2019) Genome-wide association studies of impulsive personality traits (BIS-11 and UPPSP) and drug experimentation in up to 22 861 adult research participants identify loci in the *CACNA1I* and *CADM2* genes. J Neurosci 39:2662–2618.

Scott SP, De Souza MJ, Koehler K, Petkus DL, Murray-Kolb LE (2016) Cardiorespiratory fitness Is associated with better executive function in young women. Med Sci Sports Exerc 48:1994–2002.

Smith AL, Hoza B, Linnea K, McQuade JD, Tomb M, Vaughn AJ, Shoulberg EK, Hook H (2013) Pilot physical activity intervention reduces severity of ADHD symptoms in young children. J Atten Disord 17:70–82.

Steele CC, Pirkle JRA, Kirkpatrick K (2017) Diet-induced impulsivity: effects of a high-fat and a high-sugar diet on impulsive choice in rats. PLoS One 12:e0180510.

Steele CC, Steele TJ, Gwinner M, Rosenkranz SK, Kirkpatrick K (2021) The relationship between dietary fat intake, impulsive choice, and metabolic health. Appetite 165:105292.

Stover PJ, Field MS (2015) Vitamin B-6. Adv Nutr 6:132–133.

Strickland JC, Johnson MW (2021) Rejecting impulsivity as a psychological construct: a theoretical, empirical, and sociocultural argument. Psychol Rev 128:336–361.

Todisco P, Meneguzzo P, Vogazianos P, Garolla A, Antoniades A, Tozzi F (2020) Relation between vitamin D and impulse behaviours in patients with eating disorder: a pilot observational study. Eur Eat Disord Rev 28:587–593.

Vaask S, Pomerleau J, Pudule I, Grinberga D, Abaravicius A, Robertson A, McKee M (2004) Comparison of the Micro-Nutrica Nutritional Analysis program and the Russian Food Composition Database using data from the Baltic Nutrition Surveys. Eur J Clin Nutr 58:573–579.

VanderBroek-Stice L, Stojek MK, Beach SRH, vanDellen MR, MacKillop J (2017) Multidimensional assessment of impulsivity in relation to obesity and food addiction. Appetite 112:59–68.

Wade NE, Kaiver CM, Wallace AL, Hatcher KF, Swartz AM, Lisdahl KM (2020) Objective aerobic fitness level and neuropsychological functioning in healthy adolescents and emerging adults: unique sex effects. Psychol Sport Exerc 51:101794.

Whiteside SP, Lynam DR (2001) The Five Factor Model and impulsivity: using a structural model of personality to understand impulsivity. Personal Individ Differ 30:669–689.

Winocour PH, Ishola M, Durrington PN (1989) Validation of the Friedewald formula for the measurement of low density lipoprotein cholesterol in insulin-dependent diabetes mellitus. Clin Chim Acta 179:79–83.

Wrzosek M, Sawicka A, Tałałaj M, Wojnar M, Nowicka G (2018) Impulsivity and vitamin D in bariatric surgery candidates. Pharmacol Rep 70:688–693.

Zuckerman M, Glicksohn J (2016) Hans Eysenck's personality model and the constructs of sensation seeking and impulsivity. Personal Individ Differ 103:48–52.