Eat2beNICE

Effects of Nutrition and Lifestyle on Impulsive, Compulsive, and Externalizing Behaviours

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D 3.1– Manuscript: Analysis of joint effects of PA and nutrition on impulsive symptoms in CoCA-PROUD

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Executive Summary

The aim of Deliverable 3.1 was to analyse joint effects of PA and nutrition on impulsive symptoms in CoCA-PROUD. Using a smartphone-based method to assess dietary patterns allowed a very granular analysis of short-term processes of PA, diet, and their interaction on impulsivity. To increase the sample size of the ADHD sample, we recruited not only participants from the CoCA PROUD study, but also from the BipoLife A1 and PROBIA study. We have completed the analysis and compiled the results in a manuscript which was submitted to the journal 'JMIR Mental Health' and published as a preprint:

> Ruf, A., Neubauer, A.B., Koch, E.D., Ebner-Priemer, U., Reif, A., & Matura, S. Ecological Momentary Assessment in Nutritional Psychiatry: Microtemporal Dynamics of Dietary Intake, Physical Activity, and Impulsivity in Adult ADHD. JMIR Preprints. 17/02/2023:46550. http://doi.org/10.2196/preprints.46550

The manuscript is inserted below as part of this report.

Ecological Momentary Assessment in Nutritional Psychiatry: Microtemporal Dynamics of Dietary Intake, Physical Activity, and Impulsivity in Adult ADHD

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Ecological Momentary Assessment in Nutritional Psychiatry: Microtemporal Dynamics of Dietary Intake, Physical Activity, and Impulsivity in Adult ADHD

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Abstract

Background: Attention-deficit/hyperactivity disorder (ADHD), a neurodevelopmental condition affecting around 2.5%-3% of adults, is characterized by impairing symptoms of hyperactivity, inattention, and impulsivity. Due to side effects and low adherence to pharmacotherapy, increasing attention is being paid to lifestyle factors, such as nutrition and physical activity (PA), as potential complementary treatment options. Previous research indicates that sugar and saturated fat intake may be linked to increased impulsivity, while protein intake and PA may be related to reduced impulsivity. However, most studies rely on cross-sectional data which lack microtemporal resolution and ecological validity, wherefore questions of microtemporal dynamics (eg, Is the consumption of foods high in sugar associated with increased impulsivity within minutes or hours?) remain largely unanswered. Mobile approaches, such as Ecological Momentary Assessment (EMA), have the potential to bridge this gap.

Objective: This study is the first to apply EMA to assess microtemporal associations between macronutrient intake, PA, and state impulsivity in daily life of adults with and without ADHD.

Methods: Over a 3-day-period, participants reported state-impulsivity 8 times per day (signal-contingent), recorded food and drink intake (event-contingent), and wore an accelerometer. Multilevel two-part models were used to study the association between macronutrient intake, PA, and the probability to be impulsive as well as the intensity of impulsivity (NADHD=36, Ncontrol=137).

Results: No association between macronutrient intake and state-impulsivity was found. PA was not related to the intensity of impulsivity, but to the probability to be impulsive (ADHD: ß=-0.09, 95% CI ?0.14 to ?0.04; Control: ß=?0.03, 95% CI ?0.05 to ?0.01). No evidence was found that the combined intake of saturated fat and sugar amplified the increase in state-impulsivity and that PA alleviated the positive association between sugar or fat intake (or both) and state-impulsivity.

Conclusions: Important methodological considerations are discussed which can contribute to the optimization of future EMA protocols. EMA research in the emerging field of Nutritional Psychiatry is still in its infancy, yet, EMA is a highly promising and innovative approach as it offers insights into microtemporal dynamics of psychiatric symptomology, dietary intake, and PA in daily life.

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Keywords: impulsivity; nutrition; macronutrient intake; physical activity; ecological momentary assessment; attention-deficit/hyperactivity disorder

Introduction

Attention-deficit/hyperactivity disorder (ADHD), initially conceptualized as a neurodevelopmental disorder restricted to childhood, is now recognized as a condition persisting into adulthood, with around 2.5%-3% of adults showing clinically-relevant symptoms [1,2]. ADHD is characterized by impairing symptoms of hyperactivity, inattention, and impulsivity. Individuals with ADHD are at risk for poor academic performance [3], accidents [4], financial problems [5], and numerous further adverse outcomes (see [6] for an overview). A multimodal and multidisciplinary approach, including pharmacotherapy, cognitive behavior therapy, psychoeducation, and coaching, should be applied for the treatment of adult ADHD [6]. Yet, adult ADHD is underdiagnosed and undertreated [6], likely due to the unavailability of diagnostic services or their availability only in very few specialized facilities [7]. Despite the high efficacy of pharmacotherapy for the short-term treatment of ADHD [8], not every patient responds to medication (eg, 24% non-responder [9]), long-term effects of pharmacotherapy are understudied [8], and some studies suggest that pharmacological treatment is positively associated with symptom severity in the long term (eg, [10]). Furthermore, pharmacotherapy is associated with several side effects, such as increased heart rate and blood pressure [11], reduced appetite [12] as well as sleep problems (for an overview, see [13]), and adherence to pharmacological treatment is often low (eg, [14]). These disadvantages and challenges of pharmacotherapy highlight the need for easily accessible complementary treatment options for adults with ADHD. Lifestyle factors, such as nutrition and physical activity (PA), might be promising targets for the development of complementary treatments [15–17].

Nutrition, Impulsivity, and ADHD

While it is well known that nutrition has a significant impact on physical health, evidence is growing that nutrition also plays an important role in mental health and mental functioning, wherefore the emerging field of Nutritional Psychiatry is attracting growing attention [18]. For instance, the Mediterranean diet seems to have protective effects against depressive symptoms (eg, [19]) and may even be an effective treatment strategy for depression (eg, [20]). Increasing attention is also being paid to the role of nutrition in ADHD (for overviews, see [15,17]). Del-Ponte and colleagues conducted a meta-analysis and found that healthy dietary patterns were associated with a decreased risk for ADHD (OR: 0.65; 95% CI 0.44 to 0.97), whereas unhealthy dietary patterns were related to an increased risk for ADHD (OR: 1.41; 95% CI 1.15 to 1.74) [21]. The authors conclude that the findings suggest that healthy diets rich in fruits and vegetables can protect against ADHD, while diets high in refined sugar and saturated fat can increase the risk [21]. These findings are confirmed by a recent meta-analysis which found that healthy dietary patterns characterized by fruits, vegetables, and fish were associated with a reduced risk for ADHD (OR: 0.63; 95% CI 0.41 to 0.96), while Western dietary patterns consisting of red meat, processed meat, animal fat, and salt (OR: 1.92; 95% CI 1.13 to 3.26) and junk food dietary patterns including sweets, sweetened beverages, snacks, ice creams, and fast foods (OR: 1.51; 95% CI 1.06 to 2.16) were found to be associated with an increased risk for ADHD [22]. A positive association between total sugar intake (ie, from sugar-sweetened beverages as well as dietary sources) and the risk of ADHD was found in another meta-analysis [23]. While these meta-analytical findings support the presence of a link between nutrition and ADHD, most of the included studies do not allow causal conclusions. Cross-sectional studies do not provide information on the directionality of the association and lack microtemporal resolution and ecological validity. More studies of high quality (eg, [micro-]randomized controlled trials) are needed to gain insights into causality and underlying mechanisms. Since ADHD symptomology is dynamic in nature [24], studies of high temporal resolution and ecological validity incorporating digital and mobile approaches (eg, Ecological Momentary Assessment [EMA] studies) are required to obtain evidence on short-term, microtemporal associations in daily life.

Evidence indicates that nutrition is not only associated with ADHD per se, but also with core

symptoms of ADHD, such as impulsivity and executive dysfunction. Impulsivity is a multidimensional construct [25] which manifests as “impatience, acting without thinking, spending impulsively, starting new jobs and relationships on impulse, and sensation seeking behaviours” [26] (p. 6). Impulsivity is closely linked to impaired executive function [27]. Accordingly, the concepts of impulsivity (eg, [27]) and executive dysfunction (eg, [28]) have been used to describe the same impairments in ADHD. A cross-sectional study among a non-clinical adult sample found an association between fast-food consumption and greater impulsivity (ie, delay discounting − a behavioral measure of impulsivity) [29]. Yet, directionality remains unclear. Further studies in non-clinical samples of young adults found an association between a Western-style diet high in saturated fat and added sugar and greater trait-impulsivity, with hypothesized bidirectional causation [30], and a relationship between stronger inhibitory control and less consumption of foods high in saturated fat [31]. Research in rodents provides first evidence on the causality of the relationship between nutrition and impulsivity by showing that a high-fat/high-sugar diet increases impulsivity [32,33].

Contrary to fat and sugar intake, protein intake seems to have beneficial effects on executive function. A randomized controlled dietary intervention trial in healthy men found improved reaction times on the Go/No-Go task, a measure of response inhibition and a proxy for impulsivity, in the group that followed a high protein diet for 3 weeks [34]. Tryptophan, an essential amino acid and precursor to serotonin found in almost all proteins, has been discussed as a potential underlying mechanism. For instance, it was found that the dietary intake of tryptophan was associated with lower levels of one facet of emotion-related impulsivity (ie, Pervasive Influence of Feelings) [35].

While many studies assess the relationship between ADHD symptomology or impulsivity and long-term dietary exposure (eg, habitual food intake captured through food frequency questionnaires [FFQs]), there is also some evidence that the intake of certain macronutrients has short-term effects on executive function. For instance, Brandley and Holton showed that a nutritionally balanced breakfast with optimal macronutrients-ratio (ie, 25% fat, 45% carbohydrate, and 29% protein) improved executive function of college students with and without ADHD an hour after consumption [36].

Physical Activity, Impulsivity, and ADHD

Not only nutrition, but also PA seems to influence impulsivity and executive function, as such that PA is associated with reduced impulsivity. A meta-analysis found a significant overall effect of acute, but not chronic physical exercise on executive functions in children, adolescents, and young adults [37]. Several meta-analyses studied the effect of exercise on cognition and behavior in children with ADHD showing that exercise has positive effects on executive functions [38–40]. Research assessing the effect of PA in adults with ADHD remains limited [38,41]. Yet, first findings are promising. For instance, a cross-sectional pilot study found that adults with ADHD who engaged in frequent aerobic PA reported significantly lower levels of behavioral impulsivity [42]. Beyond that, first evidence indicates that non-cardio PA (ie, Whole Body Vibration) has positive effects on cognitive functioning in adults with ADHD [43,44]. A study in college students with and without ADHD showed that in those with ADHD inhibitory performance, one aspect of executive function, improved due to acute exercise–however–all aspects of executive functions improved in those without ADHD [45]. In a study following a counterbalanced repeated measures design with a control condition, adults with ADHD improved reaction times in congruent and incongruent trials of the flanker task after 30 minutes of continuous stationary cycling, indicating benefits of acute exercise [46].

Objectives

ADHD is characterized by dynamic symptoms which manifest as states of hyperactivity, inattention, and impulsivity [24]. Yet, most studies rely on cross-sectional data which lack microtemporal

resolution and do not provide evidence with regards to true temporal associations. Retrospective reports (eg, FFQs, trait questionnaires) are prone to cognitive biases – potentially, in particular in individuals with ADHD – and overlook fluctuations of ADHD symptoms [47]. It remains unstudied whether the intake of certain macronutrients or the engagement in PA alters impulsivity within minutes or hours in everyday life. Digital technologies can bridge this gap. Digital and mobile approaches, such as EMA, offer great potential to provide novel insights into ADHD symptomatology in daily life in order to better understand behavior and functioning on the intra-individual level [24,47]. Despite the need for studies of high temporal resolution and ecological validity and the potential of digital technologies, so far, no study has applied EMA to assess whether the intake of certain macronutrients as well as the engagement in PA are associated with changes in state-impulsivity in daily life. Therefore, the aim of this study is to apply EMA to assess short-term, microtemporal associations between macronutrient intake, PA, and state-impulsivity in daily life of adults with and without ADHD. Based on previous research, 6 research questions are elaborated: It is examined whether (1) the intake of sugar as well as (2) the consumption of saturated fats are associated with an increase in state-impulsivity and whether (3) the intake of proteins as well as (4) the engagement in PA are associated with decreased state-impulsivity. Since, there is evidence that particularly the combination of a high fat and high sugar diet is associated with ADHD and impulsivity [21,30,32], it is assessed whether (5) the combined intake (ie, the interaction) of saturated fat and sugar amplifies the increase in state-impulsivity. Intriguingly, research indicates that PA may buffer against adverse effects of fat intake on cognitive functioning [48,49]. Therefore, it is studied whether (6) PA alleviates the positive association between sugar or fat intake and state-impulsivity.

Methods

Procedure

Data were collected within the Eat2beNICE-APPetite-study which comprises 2 in-person sessions as well as an EMA period (parts of the data of this study have been used for different research questions, see [50–52]). In the first in-person session, participants completed questionnaires and received comprehensive training to familiarize with the APPetite-mobile-app which was used for the EMA period (for further details see [50]). Beyond that, body weight and body height were measured in order to calculate BMI. The study was approved by the local ethics committee. All participants declared that they understood the study procedure and signed a written informed consent.

EMA Protocol

A study smartphone was used by the participants to complete the EMA protocol of the APPetite-mobile-app for 3 consecutive days (2 weekdays and 1 weekend day). Participants received 8 semi-random signal-contingent prompts per day (between 8 AM and 10 PM, at least 1 hour in-between prompts). Each prompt assessed state-impulsivity. Prompts could be postponed for up to 25 minutes. Participants were able to record food intake at any time (ie, event-contingent) through the incorporated APPetite-food record. Beyond that, a time-contingent prompt at 9 p.m. asked participants whether all foods and drinks of the day have been recorded. Further details on the APPetite-mobile-app can be found in Ruf, Koch, et al. [50].

Sample

The Eat2beNICE-APPetite-study recruited participants from 4 existing study cohorts. Adults with ADHD were invited from (1) the PROUD (Prevention of Comorbid Depression and Obesity in Attention-Deficit/Hyperactivity Disorder) study [53], (2) the BipoLife-A1 study which follows up

individuals with an increased risk for bipolar disorders, including patients affected by ADHD or depression (or both) [54,55], and (3) the PROBIA study which recruited patients with ADHD or borderline personality disorder (or both) [56]. Healthy controls were recruited from the LORA (Longitudinal Resilience Assessment) study which enrolled individuals not affected by psychiatric conditions and follows them up since 2016 [57].

In total, 43 adults with and 185 without ADHD participated in the study. After the first in-person session, 4 participants without ADHD dropped out because of personal reasons (eg, spontaneous vacation) or due to the inability to respond to prompts (eg, because of work commitments). Data of 1 participant without ADHD were excluded as they proved to be untrue. Data of 26 participants without as well as 6 with ADHD were excluded due to poor records of food intake (eg, only 1 meal recorded). One participant of the ADHD sample had to be excluded because no PA data could be retrieved due to technical problems. One participant without ADHD was excluded because BMI was unavailable due to malfunction of the scales. Furthermore, 16 participants without ADHD had to be excluded from analyses as they showed no variation in state-impulsivity across prompts (ie, all MIS items consistently answered with *1 – not applicable*). The final sample includes 36 participants with and 137 without ADHD. Demographics of the ADHD and control sample are shown in Table 1.

Table 1. Demographics of the sample with and without ADHD.

	ADHD sample (n=36)	Control sample (n=137)
Gender, n (%)		
Female	19 (52.8)	100 (73)
Male	17 (47.2)	37 (27)
Age (years), mean (SD)	35.25 (12.04)	28.8 (7.72)
BMI, mean (SD)	29.06 (7.87)	24.08 (4.14)

Measures

Macronutrient Intake

Macronutrient intake was captured based on the APPetite-mobile-app which comprises a food record [50]. The food recording follows a 6-step process: (1) selection of meal type, (2) entry of time of intake, (3) selection of consumed foods and drinks, (4) specification of consumed amounts, (5) presentation of reminder for commonly forgotten foods, and (6) indication of predominant reason for eating or drinking. Participants were instructed to record foods and drinks as soon as possible after consuming them. For the generation of nutritional values (ie, sugar, saturated fat, and protein intake), the collected food entries were transferred to myfood24-Germany [58] by trained staff. A feasibility, usability, and validation study was conducted to evaluate the APPetite-mobile-app. Findings indicated that the APPetite-mobile-app is a feasible and valid dietary assessment tool which is likely more accurate compared to 24-hour recalls [50].

State-Impulsivity

State-impulsivity was assessed using the Momentary Impulsivity Scale (MIS) [59]. The MIS captures state-impulsivity on basis of 4 items which each comprises a statement (eg, “I said things without thinking”). Participants rated how well each statement described their behavior, cognition, and experiences since the last prompt or since waking up in the first daily prompt on a 5-point scale. A sum score of the items was calculated. Higher values indicate greater state-impulsivity. Note that the original response scale (1=very slightly or not at all; 2=a little; 3=moderately; 4=quite a bit;

5=extremely) was slightly altered during translation (translate-back-translate-procedure with a native bilingual speaker in English and German), since the literal translation lacked differentiability. One main difference between the English and German version is that *1* on the response scale stands for *not applicable* in the German version (1=nicht zutreffend, 2=eher nicht zutreffend, 3=teils-teils, 4=eher zutreffend, 5=zutreffend). In the final datasets, McDonald's Omega of the MIS was 0.576 (within) and 0.832 (between) in the ADHD sample and 0.505 (within) and 0.768 (between) in the control sample.

Trait-Impulsivity

The UPPS-P Impulsive Behavior Scale (Urgency Premeditation Perseverance and Sensation Seeking Impulsive Behavior Scale) [60] was used to assess trait-impulsivity based on 59 items. Each item described a statement (eg, "I have trouble controlling my impulses"). Participants reported how well each statement described them on a 4-point-scale from *agree strongly* to *disagree strongly*. The UPPS-P assesses impulsivity as a multi-faceted construct which includes the following subscales: negative urgency (12 items), positive urgency (14 items), (lack of) premeditation (11 items), (lack of) perseverance (10 items), and sensation seeking (12 items). The German translation of the items for the scales negative urgency, (lack of) premeditation, (lack of) perseverance, and sensation seeking were taken from Schmidt et al. [61]. The items of the subscale positive urgency were translated through the translate-back-translate-procedure. In the present samples, internal consistency was α_{ADHD}=.92 and $\alpha_{control}$=.89 for negative urgency, α_{ADHD}=.81 and $\alpha_{control}$=.75 for premeditation, α_{ADHD}=.83 and $\alpha_{control}$=.83 for perseverance, α_{ADHD}=.89 and $\alpha_{control}$=.85 for sensation seeking, and α_{ADHD}=.93 and $\alpha_{control}$=.92 for positive urgency.

Physical Activity

PA was captured objectively using move 3 sensors (movisens GmbH, Karlsruhe, Germany). Participants wore the sensor on the non-dominant wrist during the EMA period – day and night. The software DataAnalyzer (movisens GmbH, version 1.13.7) was used to calculate the movement acceleration intensity per minute (mg/min) from raw accelerometry. Non-wear time was excluded from analysis.

Data Pre-Processing

Thirteen single days of the control sample had to be excluded due to poor or incomplete dietary data. Data pre-processing was completed based on the time intervals, for which state-impulsivity was assessed (ie, time between current prompt and previous prompt/waking up). To study the association between macronutrient intake, PA, and state-impulsivity, each of these time interval was matched to concurrent sugar, saturated fat, and protein intake as well as mean PA (ie, mean movement acceleration). Concurrent intake was defined as the sum of any intake of sugar, saturated fat, or protein within the respective time interval. Based on the movement acceleration intensity per minute (mg/min), mean movement acceleration was calculated for each time interval in which the sensor was worn at least 2 thirds of the time.

The Level-1 predictors sugar, fat, and protein intake as well as PA were person-mean centered in order to produce unbiased estimates of the within-person effect [62]. To avoid estimation problems due to substantial differences in variance of the predictors and the outcome, the Level-1 predictors were divided by 10. The Level-2 covariates age and BMI were centered around 30 and 25, respectively, to make the model intercept more interpretable as recommended by Viechtbauer [63]. Grand-mean-centering was used for the Level-2 covariate trait-impulsivity. The Level-2 covariate gender was coded as 0 (male) and 1 (female).

The MIS items were not completed in 401 time intervals ($n_{control}$=297; n_{ADHD}=104) which were therefore excluded. Due to the semi-random sampling protocol, time intervals varied in length.

Beyond that, the option to postpone prompts and the assessment of state-impulsivity “since waking up” in the first prompt produced rather short or long time intervals. Since we do not expect an effect of macronutrient intake as well as PA on state-impulsivity within less than 15 minutes (cf. [64]) and are interested in short-term associations, time intervals shorter than 15 minutes ($n_{control}$=21; n_{ADHD}=8) and longer than 3 hours ($n_{control}$=118; n_{ADHD}=27) were excluded. Beyond that, time intervals in which the Level-1 predictor PA was not available (eg, due to the exclusion criteria for time intervals in which the sensor was worn less than 2 thirds of the time), were excluded ($n_{control}$=166; n_{ADHD}=73). The final dataset includes 629 time intervals in the ADHD and 2,464 in the control sample and is provided in the online supplementary materials.

Data Analysis

Due to the nested data structure (time intervals [Level 1] nested within individuals [Level 2]), multilevel models were needed for analyses. The MIS score, the outcome of this study, showed a strongly right-skewed distribution which did not meet the assumptions of linear multilevel modelling. Furthermore, due to a significant proportion of the lowest MIS score (all items answered with 1 *not applicable*, resulting in a MIS score of 4), a gamma multilevel model was unable to represent the right-skew in the data adequately. To account for the inflation of the lowest MIS score (ie, 4) which represents the absence of impulsivity, we used a multilevel two-part model which allows to account for zero-inflated, continuous data (ie, semicontinuous data). This type of model allows studying whether the intake of certain macronutrients and PA is associated with the occurrence of state-impulsivity (ie, is an individual impulsive at all?) and the intensity of impulsivity (ie, if an individual is impulsive, how impulsive are they?). In order to move the inflation from 4 to 0, the 5-point-scale of the MIS was re-coded (1 to 0, 2 to 1, 3 to 3, 4 to 3 and 5 to 4). The model we applied combines a multilevel logistic regression in the zero part to study the occurrence of state-impulsivity and a multilevel gamma regression (to account for the right-skew in the positive values) in the continuous part of the model to assess the intensity of state-impulsivity. The model does not only allow to study the occurrence and intensity of state-impulsivity but also accounts for the potential dependency between the 2 outcome components, by modelling a cross-part correlation. While logistic regressions typically predict the outcome to be 1, the multilevel logistic regression in the zero part of the model used in this study predicts no impulsivity (outcome=0), that is, the probability not to be impulsive in a given individual in a given time interval.

To examine the associations between macronutrient intake, PA, and state-impulsivity (research question 1 to 4), a model with the Level-1 predictors sugar, saturated fat, and protein intake as well as PA in both model parts (ie, the logistic regression as well as the gamma regression) was run. A joint model was chosen in order to control for the other predictors, since the intake of different macronutrients as well as PA naturally does not take place in isolation, but in combination. Following, the interaction between the Level-1 predictors sugar and fat intake was added to both model parts (research question 5). Finally, a model including the interaction between sugar intake, fat intake, and PA (ie, 4 interactions modelled: 2-way-interactions between sugar intake and PA, between fat intake and PA, between sugar and fat intake and 3-way-interaction between sugar intake, fat intake, and PA) in both model parts was run (research question 6). In all models, the Level-2 covariates gender, age, BMI, and trait-impulsivity were included. All models included random intercepts in both model parts (ie, we expect individuals to differ in their average probability not to be impulsive and the average intensity of state-impulsivity) and random slopes for all Level-1 predictors (and their interaction) to examine whether the effects differ between individuals. The 3 models were run separately for the ADHD and the control sample.

All models were estimated using the R-package brms [65,66] which supports Bayesian multilevel modelling. Credible intervals (95% CI) of fixed effects that do not include 0 were interpreted as significant effects. Since nonpositive estimates for standard deviations (SD) are not allowed, lower limit of the CI of random effects that are equal to 0.00 suggest that the random effect is not

significant (ie, that individual differences in the intercept, the effects of the Level-1 predictors, or the interactions between Level-1 predictors are small and possibly not statistically meaningful). Details on the model used in this study (eg, implementation and interpretation) can be found in Ruf, Neubauer, et al. [51].

The estimation of model parameters was based on 10,000 iterations. The initial values for the sampler were set to 0 (*init=0*) and maximum treedepth was set to 11 to reach convergence in 2 models (see open R code provided in Multimedia Appendix 2). The default settings of all other sampling and prior parameters were maintained. R version 4.2.2 [67], RStudio version 2022.7.2.576 [68], brms version 2.18.0, and rstan version 2.26.13 [69] were used to perform the analyses.

Results

Descriptive Findings

Descriptive statistics of the Level-1 predictors sugar, saturated fat, and protein intake as well as PA and the Level-2 covariate trait-impulsivity for the ADHD sample and the control sample are shown in Table 2. Participants reported not to be impulsive (ie, MIS=0) in 180/629 time intervals (28.6%) in the ADHD sample and in 1,434/2,464 time intervals (58.2%) in the control sample. Within time intervals in which participant reported to be impulsive (n_{ADHD}=449, $n_{control}$=1,030), state-impulsivity was rated on average 3.9 (SD 2.6) in the ADHD sample and 2.8 (SD 1.9) in the control sample on the shifted response scale (ranging from 0 to 16). To test whether individuals with and without ADHD differ in the occurrence and the intensity of impulsivity, a multilevel two-part model with the Level-2 predictor ADHD diagnosis (0=no ADHD, 1=ADHD) including all participants was calculated (see Model 0 in the open R code provided in Multimedia Appendix 2). Results showed that individuals with ADHD were less likely not to be impulsive (ie, significant fixed effect of ADHD diagnosis in the zero part: −1.69, SE 0.32, 95% CI −2.34 to −1.06) and reported significantly higher levels of impulsivity intensity (ie, significant fixed effect of ADHD diagnosis in the continuous part: 0.36, SE 0.08, 95% CI 0.20 to 0.51) compared to individuals without ADHD.

Table 2. Descriptive statistics of the Level-1 predictors ($n_{control}$=2,464; n_{ADHD}=629) and Level-2 covariate trait-impulsivity ($n_{control}$=137; n_{ADHD}=36).

	ADHD sample		Control sample	
	Mean/*Mdn*[a]	SD	Mean/*Mdn*	SD
Level-1				
sugar intake in g	10.19 / 0	17.50 (overall) 5.71 (between)	9.87 / 1.04	15.94 (overall) 4.41 (between)
saturated fat intake in g	4.46 / 0	8.97 (overall) 2.39 (between)	4.47 / 0.03	7.92 (overall) 2.11 (between)
protein intake in g	10.42 / 0	20.34 (overall) 4.95 (between)	9.93 / 0.64	16.73 (overall) 4.13 (between)
PA (acceleration) in mg	130.85 / 120.63	77.07 (overall) 38.04 (between)	144.68 / 134.13	78.77 (overall) 31.68 (between)
Level-2				
trait-impulsivity	30.24 / 30.1	5.08	23.78 / 23.4	3.68

[a]median. Medians are included to highlight that the Level-1 predictors follow skewed distributions and are zero-inflated (i.e., food intake did not occur within each time interval, wherefore macronutrient intake is equal to zero).

Average compliance with the signal-contingent prompts (ie, percentage of complete prompts within received prompts) was 89.6 (SD 12.4) in the ADHD and 90.3 (SD 11.5) in the control sample (not including participants and days that were excluded as a whole, but including time intervals that were

excluded from final analyses based on interval length and missing PA/MIS).

Findings From the Multilevel Two-Part Models

Since the estimates of the continuous part (ie, the gamma regression) of the multilevel two-part model are modelled on the log scale, the exponential is used to obtain estimates in the original metric. In the zero part (ie, the logistic regression), estimates are modelled on the logit scale. The intercept of the zero part represents the average log-odds of no impulsivity across all participants when all predictors are 0. The inverse logit function (eg, the *plogis*-function in R) can be used to transform the log-odds to the probability not to be impulsive. Predictor estimates in the zero part represent the expected change in log-odds of no impulsivity for a 1-unit increase in each predictor respectively. To obtain the expected change in the probability not to be impulsive, the probability of the intercept (ie, *plogis*(intercept)) can be compared to the predicted probability when the respective predictor takes on a certain value (eg, if the chosen value of the predictor is 1, the predicted probability is *plogis*(intercept + fixed effect of the predictor)).

Sugar, Saturated Fat, and Protein Intake, PA, and State-Impulsivity

Results of the model including fixed and random effects for sugar, saturated fat, and protein intake as well as PA in both model parts are shown in Table 3 for the ADHD sample. The intercept of the zero part indicates that the mean probability not to be impulsive is 11.7% (*plogis*(−2.02)), when all predictors and covariates are equal to zero. Sugar, saturated fat, and protein intake have no significant fixed effect on the probability not to be impulsive. However, the effect of saturated fat and protein intake on the probability of no impulsivity differs across individuals with a *SD* of 0.29 and 0.22, respectively. In time intervals in which PA is 1 unit (=10 mg) above zero (ie, above the person mean) and all other predictors are zero, the probability not to be impulsive is 10.8% (*plogis*(−2.02−0.09)), that is, a 1-unit increase in PA is associated with a decrease in the probability not to be impulsive of 0.9% (11.7%-10.8%) when all other predictors are zero. This indicates that higher levels of PA are associated with a higher probability to be impulsive. The intercept of the continuous part of the model demonstrates that, when all predictors and covariates are equal to zero, participants with ADHD report an average impulsivity intensity of 3.32 ($e^{1.20}$). There is no significant fixed effect of sugar, saturated fat, and protein intake as well as PA. Accordingly, the intake of sugar, saturated fat, and protein intake as well as the level of PA are not associated with the intensity of state-impulsivity. There is a negative cross-part-correlation (−.38, SE 0.17, 95% CI −0.68 to −0.03) indicating that individuals who are impulsive more often, are more impulsive when they are impulsive suggesting that the frequency and intensity of impulsivity correlate.

Table 3. Model estimates of the multilevel two-part model including fixed and random effects for sugar, saturated fat, and protein intake as well as PA in both model parts in the ADHD sample.

	Zero part				Continuous part			
	Estimate	SE	95% CI[a]		Estimate	SE	95% CI	
			LL[b]	UL[c]			LL	UL
				Model 1:				
Fixed effects								
intercept	−2.02	0.55	−3.14	−0.97	1.20	0.12	0.96	1.44
sugar intake	−0.01	0.10	−0.22	0.18	0.01	0.02	−0.03	0.04
sat. fat intake[d]	−0.10	0.29	−0.70	0.45	0.01	0.04	−0.07	0.10
protein intake	−0.09	0.14	−0.38	0.16	−0.02	0.02	−0.05	0.01
PA	−0.09	0.03	−0.14	−0.04	0.00	0.00	−0.00	0.01
gender	0.40	0.74	−1.04	1.89	−0.15	0.17	−0.48	0.20
age	−0.02	0.04	−0.09	0.05	0.00	0.01	−0.01	0.02
BMI	0.11	0.05	0.01	0.20	0.00	0.01	−0.02	0.02

trait-impulsivity	−0.11	0.07	−0.24	0.03	0.03	0.02	0.00	0.07
Random effects								
SD(intercept)	1.83	0.32	1.29	2.55	0.44	0.06	0.33	0.58
SD(sugar intake)	0.12	0.09	0.00	0.34	0.03	0.02	0.00	0.07
SD(sat. fat intake)	0.29	0.24	0.01	0.89	0.04	0.03	0.00	0.11
SD(protein intake)	0.22	0.14	0.01	0.55	0.02	0.01	0.00	0.04
SD(PA)	0.06	0.04	0.00	0.14	0.01	0.01	0.00	0.03

[a]credible interval
[b]lower limit
[c]upper limit
[d]saturated fat intake

Table 4 shows the results of the same model (ie, fixed and random effects for sugar, saturated fat, and protein intake as well as PA in both model parts) for the control sample. Individuals without ADHD had a mean probability not to be impulsive of 69.2% (*plogis*(0.81)), when all predictors and covariates are equal to zero. Just like in the ADHD sample, sugar, saturated fat, and protein intake had no significant fixed effect on the probability not to be impulsive. However, contrary to the ADHD sample, the effects of saturated fat and protein intake on the probability not to be impulsive did not differ across individuals without ADHD. Yet, higher levels of PA were also associated with a higher probability to be impulsive in adults without ADHD. Accordingly, the probability not to be impulsive is 68.6% (*plogis*(0.81−0.03)) in time intervals in which PA is 1 unit (=10 mg) above zero (ie, above the person mean) and all other predictors are zero. Consequently, a 1-unit increase in PA is associated with a decrease in the probability not to be impulsive of 0.6% (69.2%-68.6%) when all other predictors in the model are zero. Again, the cross-part-correlation (−.53, SE 0.09, 95% CI −0.69 to −0.33) is negative indicating that individuals, who are impulsive more often, are more impulsive when they are impulsive.

Table 4. Model estimates of the multilevel two-part model including fixed and random effects for sugar, saturated fat, and protein intake as well as PA in both model parts in the control sample.

	Zero part				Continuous part			
	Estimate	SE	95% CI[a]		Estimate	SE	95% CI	
			LL[b]	UL[c]			LL	UL
				Model 2:				
Fixed effects								
intercept	0.81	0.27	0.28	1.35	0.68	0.07	0.54	0.83
sugar intake	−0.02	0.04	−0.10	0.06	−0.01	0.01	−0.04	0.02
sat. fat intake[d]	−0.04	0.11	−0.25	0.18	0.00	0.04	−0.07	0.08
protein intake	−0.04	0.05	−0.13	0.06	−0.02	0.02	−0.05	0.02
PA	−0.03	0.01	−0.05	−0.01	0.01	0.00	0.00	0.02
gender	−0.52	0.33	−1.17	0.12	0.17	0.09	−0.00	0.34
age	−0.02	0.02	−0.05	0.02	−0.00	0.00	−0.01	0.01
BMI	0.03	0.04	−0.04	0.11	0.00	0.01	−0.02	0.02
trait-impulsivity	−0.20	0.04	−0.27	−0.13	0.05	0.01	0.03	0.07
Random effects								
SD(intercept)	1.44	0.12	1.22	1.69	0.33	0.03	0.27	0.39
SD(sugar intake)	0.06	0.04	0.00	0.17	0.03	0.02	0.00	0.06
SD(sat. fat intake)	0.14	0.10	0.00	0.38	0.05	0.04	0.00	0.14
SD(protein intake)	0.05	0.04	0.00	0.15	0.02	0.02	0.00	0.06
SD(PA)	0.07	0.02	0.04	0.10	0.01	0.01	0.00	0.02

[a]credible interval
[b]lower limit
[c]upper limit

[d]saturated fat intake

Interaction Between Sugar and Saturated Fat Intake

To study whether the combined intake of saturated fat and sugar amplifies the effect of sugar and saturated fat intake on state-impulsivity, the interaction between the Level-1 predictors sugar and fat intake was added to both model parts. Results of the ADHD sample are shown in Supplementary Table 1, results of the control sample in Supplementary Table 2. In both samples and both model parts, the interaction between sugar and saturated fat intake was not significant. However, in the ADHD sample, the interaction effect between sugar and saturated fat intake on the probability not to be impulsive varied across participants with a *SD* of 0.25 in the zero part.

Buffering Effect of PA on the Association Between Sugar and/or Fat Intake and State-Impulsivity

In order to test whether PA alleviates the positive association between sugar and/or fat intake and state-impulsivity, a model including the interaction between sugar intake, fat intake, and PA (ie, 4 interactions: 2-way-interactions between sugar intake and PA, between fat intake and PA, between sugar and fat intake and 3-way-interaction between sugar intake, fat intake and PA) in both model parts was run for each sample. Supplementary Table 3 comprises the results of the ADHD and Supplementary Table 4 of the control sample. In both samples, the 4 interactions in the zero as well as the continuous part of the model were not significant. Only in the ADHD sample, the interaction effect of sugar and saturated fat intake (as in the previous model) and the 3-way interaction between sugar and saturated fat intake and PA varied significantly between participants with ADHD.

Discussion

While impulsivity, a core symptom of ADHD, can contribute to the disruption of daily functioning, first evidence indicates that the intake of certain macronutrients as well as the engagement in PA might alter impulsivity and executive function. Yet, despite the potential of digital and mobile technologies, studies of high temporal resolution and ecological validity are lacking and it remains unanswered whether the intake of certain macronutrients as well as the engagement in PA are associated with short-term changes in state-impulsivity in everyday life. Therefore, this study applied EMA to assess short-term, microtemporal dynamics of macronutrient intake, PA, and state-impulsivity in daily life of adults with and without ADHD. Contrary to previous findings which suggest that the intake of sugar and saturated fat is associated with greater impulsivity, whereas the intake of proteins is linked to decreased impulsivity and improved executive function, no association between macronutrient intake and state-impulsivity (ie, the probability to be impulsive as well as the intensity of impulsivity) was found in this study. However, some between-person variability was observed. Furthermore, in contrast to prior research indicating that PA is associated with reduced impulsivity, no relationship between PA and the intensity of impulsivity was found and PA was associated with an increased probability to be impulsive in both samples. No evidence was found that the combined intake of saturated fat and sugar amplified the increase in state-impulsivity and that PA alleviated the positive association between sugar or fat intake and state-impulsivity.

One reason for not finding an association between macronutrient intake and state-impulsivity in this study could be the (varying) length of the time intervals in which the association was studied. In this context several methodological considerations need to be discussed: (1) Assessment of state-impulsivity – Since 3 items of the MIS describe specific actions (“I said things without thinking”, “I spent more money than I meant to”, “I made a ‘spur of the moment’ decision”), the assessment has to be based on time intervals (here “since the last prompt”). Only the item “I have felt impatient” could be adapted to allow an assessment on the momentary level (ie, “Right now I feel impatient”). A

momentary assessment would allow to specify time intervals prior to the impulsivity assessment more flexibly in order to study the temporal sequence of the association. (2) Lengths of time intervals – A semi-random signal-contingent EMA protocol was used to assess state-impulsivity, so that participants could not predict the exact time of the next prompt. This allows capturing a better reflection of the participants' daily lives. However, it results in time intervals of different lengths (with at least 1 hour in-between 2 prompts in this study). Yet, the first assessment of each day assessing state-impulsivity "since waking up" and the postponement of prompts, led to even shorter or rather long time intervals. As a result, the length of time intervals varied considerably. For this reason, time intervals shorter than 15 minutes and longer than 3 hours were excluded from analysis. (3) Temporal manifestation of the effect of macronutrients – Research providing evidence regarding the time frame in which macronutrients affect cognition and behavior is still lacking. Beyond that, the time frame, in which the effects show, might differ across macronutrients.

Since the assessment of impulsivity was based on time intervals, this study was restricted to assessing the association between state-impulsivity and macronutrient intake within each time interval for which impulsivity was assessed (ie, impulsivity and concurrent macronutrient intake, not intake and subsequent impulsivity). Considering time intervals were of rather different length (15 minutes to 3 hours), the approach of this study might overlook the effect of macronutrient intake. As it is not yet clear within which time frame specific macronutrients affect cognition and behavior, controlled studies are needed to establish the temporal manifestation of the effects of macronutrients on impulsivity. This knowledge is required to adjust EMA protocols to study the relationship between macronutrient, PA, and state-impulsivity more systematically. For instance, a time-contingent assessment of state-impulsivity could be considered to obtain time intervals of similar length (eg, prompts every hour). The intervals between prompts should be determined on basis of the novel input and evidence that controlled studies can offer in terms of the temporal manifestation of short-term macronutrients' effects on impulsivity.

Also important in this context is the operationalization of state-impulsivity. This study used a self-report measure to capture state-impulsivity. Yet, it remains unclear whether macronutrient intake alters impulsivity as such, or whether the effect of macronutrients might only affect sub-domains (eg, response inhibition). Future studies should include impulsivity-related behavioral measures (eg, stop-signal task), which also open up the opportunity to assess impulsivity momentarily. The momentary assessment of impulsivity, in turn, enables to assess the temporal sequence of the association. Beyond that, it can contribute to establishing time windows within which macronutrients might affect state-impulsivity, since the length of time intervals, within which the association is studied, can be set independently.

Even though, no overall association between macronutrient intake and state-impulsivity was found, some variation (ie, individual differences) in the effect of certain macronutrients was observed, particularly in the ADHD sample. Muth and Park point out that age, PA, and glucose metabolism are potential factors contributing to individual differences in the macronutrient-cognition relationship [70]. In this study, PA was not found to moderate the relationship between sugar/fat intake and state-impulsivity. However, future studies should aim at identifying factors that moderate the macronutrient-impulsivity relationship. In this context, continuous glucose monitoring could be a feasible and promising addition to future EMA studies.

Against expectation, PA was not associated with reduced impulsivity (ie, lower probability to be impulsive and decreased intensity of impulsivity), but with an increase in the probability to be impulsive in adults with and without ADHD. Yet, it is important to note that temporal associations do not reflect causality. For instance, an individual might experience a state of impulsivity and as a consequence actively decide to engage in PA as a counteracting measure, resulting in a positive association between PA and the probability to be impulsive. Hence, the observed association does not imply that engaging in PA leads to a higher probability to be impulsive. Beyond that, these findings might be a result of the operationalization of PA. Using the mean acceleration within time intervals

might average out relevant fluctuations in PA intensity. Hence, it cannot be differentiated between time intervals in which an individual shows low levels of PA continuously and time intervals in which an individual engages in some moderate-to-vigorous PA but is inactive the remainder of the time. However, particularly acute PA has been shown to have positive effects on executive function [71–75], whereas taking the mean PA might overlook the association between PA and state-impulsivity. Yet, since time intervals differed considerably in length, the mean acceleration was the most straightforward operationalization of PA in this study. Future EMA studies should consider implementing a sampling approach which yields time intervals of similar length (see above), in order to allow the operationalization of PA as minutes engaged in different PA intensities (eg, minutes of moderate-to-vigorous PA). Beyond that, the differentiation between exercise and non-exercise PA could allow further insights, as found for the effect of PA on mood [76]. A further explanation for the positive association between PA and the probability to be impulsive could be the nature of the MIS items. For instance, being impatient could manifest as walking up and down or twiddling with something. Spending more money than intended might be more likely to occur when being out and about (eg, walking around the city). This further highlights the importance of differentiating between different PA intensities and between exercise and non-exercise PA in future studies.

Strengths and Limitations

This study is, to the best of our knowledge, the first to assess the relationship between macronutrient intake, PA, and state-impulsivity in daily life using EMA. This kind of research is innovative and highly important to better understand fluctuations of ADHD symptomology in daily life and provides novel evidence of high temporal resolution and ecological validity which is highly relevant to the growing field of Nutritional Psychiatry. Yet, the findings of this study should be interpreted in the light of some limitations: (1) The assessment of impulsivity as well as food intake is based on self-reports. However, participants might be less likely to report foods and drinks and respond to prompts when being (more) impulsive, which might have caused some bias (ie, systematic non-compliance). Therefore, more objective assessments of dietary intake (eg, passive detection of eating events [77] and automatized photo-based dietary assessment) and impulsivity (eg, passive detection of impulsive behavior [78]) are desirable. However, even though self-reports are generally prone to bias, particularly self-reports of food intake [79], assessing food intake in real time or near real time, as done in this study, minimizes recall biases compared to typically used retrospective dietary assessments (eg, FFQs). Beyond that, the smartphone app used for the dietary assessment in this study, the APPetite-mobile-app, was subject to a validation study, which showed that the app assessed food intake more accurately compared to widely used 24-hour recalls [50]. (2) This study neither allows to establish temporal sequences nor causal relationships. While EMA studies are essential to shed light on ecologically valid microtemporal associations between macronutrient intake, PA, and state-impulsivity, complementary controlled studies are needed to gain insights into the directionality of short-term effects of macronutrients and PA on state-impulsivity.

Three strengths of this study are (1) the objective assessment of PA, (2) the application of sophisticated statistical models (ie, multilevel two-part models), and (3) the inclusion of adults with and without ADHD. For instance, Abramovitch et al. [42] used a self-report questionnaire to capture PA, even though 2 systematic reviews indicate that indirect measures of PA (ie, self-reports) are unsatisfactory given that they differ substantially from direct, objective measures, such as accelerometers [80,81]. Since impulsivity is widely understood as a characteristic that everyone shows some degrees of – with clinical samples such as individuals with ADHD showing particularly high levels – it is especially interesting to study the association between macronutrient intake, PA, and state-impulsivity in a clinical as well as a control sample.

Conclusions

This study is the first to apply EMA to assess short-term, microtemporal associations between macronutrient intake, PA, and state-impulsivity in everyday life of adults with and without ADHD. While EMA research in the context of Nutritional Psychiatry is still in its infancy, it is undeniably a highly promising and innovative approach to gain insights into microtemporal dynamics of psychiatric symptomology and lifestyle behaviors in daily life. This study provides and discusses important methodological considerations which can help advance the field and contribute to the optimization and tailoring of future EMA protocols. Beyond that, findings from EMA studies can help build the foundation for the development of just-in-time adaptive interventions. This type of intervention represents a key element of digital psychiatry as it provides personalized support in daily life of patients right at the time it is needed most.

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Conflicts of Interest

None declared.

Statement of Ethics

The local ethics committee of the faculty of medicine of the Goethe University Frankfurt (Ethikkommission des Fachbereichs Medizin der Goethe-Universität) approved the study (reference number: 192/18). All subjects declared that they understood the study procedure and signed a written informed consent. The study was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki, 1975).

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Author Contributions

A Ruf, EDK, UE-P, A Reif and SM designed and planned the study. A Ruf contributed to data collection, conducted the data pre-processing and data analyses and wrote the first draft of the manuscript. A Ruf and ABN contributed to data interpretation. A Ruf, ABN, EDK, UE-P, A Reif and SM critically reviewed, edited and approved the final manuscript.

Data Availability Statement

The data and R code that support the findings of this study are available in the online supplementary materials of this article.

Abbreviations

CI: credible interval
EMA: ecological momentary assessment
FFQ: Food frequency questionnaire
PA: Physical activity

SD: standard deviation

Multimedia Appendix 1

Supplementary Table 1-4.

Multimedia Appendix 2

Open R Code.

Multimedia Appendix 3

Open Data.

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Supplementary Files

Multimedia Appendixes

Supplementary Table 1-4.
URL: http://asset.jmir.pub/assets/821017e1f19ebd8cb9b71fdfba13c88c.pdf

Open R Code and Open Data.
URL: http://asset.jmir.pub/assets/195d70b4ff8fe767feebb57ad565ca4a.zip