Dietary- but not exercise-induced acute iso-energetic deficit result in short-term appetitive compensatory responses in adolescents with obesity.

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Running title: Energy deficits, appetite, and pediatric obesity.

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Abstract

Background. Producing negative energy balance rests on the creation of energy deficits that have been shown, depending on their modality, to induce potential appetitive compensatory responses. The aim of this study was to compare energy intake (EI), appetite feelings, and the hedonic responses to equivalent acute energy deficits induced by exercise *versus* energy restriction in adolescents with obesity.

Methods. In a within-participants design, seventeen adolescents with obesity (12-16 years, Tanner stage 3-5, 9 males) randomly completed three conditions: i) control (CON); ii) deficit induced by diet only (Def-EI); and iii) deficit induced by exercise only (Def-EX). Lunch was calibrated to generate a 400-kcal deficit in Def-EI and remained similar in CON and Def-EX. A 400-kcal deficit was created through a cycling bout set at 65% VO_{2peak} in Def-EX. *Ad libitum* EI, macronutrient intake and relative EI (REI) were assessed at dinner, subjective appetite sensations taken at regular intervals, and food reward measured before dinner.

Results. Food intake at dinner was greater in Def-EI (1112 ± 265 kcal) compared to CON (983 ± 277 kcal; p=0.005) and Def-EX (1009 ± 281 kcal; p=0.025). Absolute protein and lipid intake were significantly higher in Def-EI (52.4 ± 9.5g and 36.8±8.9g respectively) compared with both CON (44.9 ± 12.6g; p=0.001 and 33.8 ± 10.1g; p=0.002 respectively) and Def-EX (47.3 ± 11.8 g, p=0.018, 35.4 ± 10.1 g, p=0.036 respectively). Area under the curve (AUC) for hunger, desire to eat and prospective food consumption were significantly higher in Def-EI compared with both CON (p=0.0001) and Def-EX (p=0.0001). AUC for fullness was significantly lower on Def-EI compared with CON and Def-EX (p=0.0001). Implicit wanting for sweet food was significantly lower on Def-EX (p=0.031), relative to CON.

Conclusion. Appetitive compensatory responses that are observed after iso-caloric energy restriction in adolescents with obesity are absent with acute exercise, which could contribute to optimize our impact on short-term energy balance.

Keywords: Pediatric Obesity; Energy Restriction; Exercise; Appetite; Energy Deficit.

1. Introduction

Management and reduction of the increasing prevalence of pediatric overweight and obesity rest on the development and implementation of effective weight-loss strategies. While dietary restriction interventions are mainly used, alone or as the core element of multidisciplinary interventions, they have been shown to activate behavioral and physiological compensatory mechanisms to preserve energy stores (Thivel et al. 2021). A rise in hunger, together with an increase in ghrelin concentrations and a reduction in Peptide YY (PYY) and Glucagon-like-peptide-1 (GLP-1), have been effectively shown to favor increased food consumption in response to acute (<72 hours) energy deficits generated through energy restriction in both normal weight individuals (Alajmi et al. 2016; King et al. 2011; Thivel et al. 2018) and people with obesity (Cameron et al. 2016). These compensatory responses to energy restriction might contribute to reduce the efficacy of weight loss interventions and to the weight regain that is usually observed. Physical exercise, in contrast, has been shown to potentially counteract and mitigate these compensatory appetitive responses, optimizing the effect of interventions on patients' energy balance (Thivel et al. 2021). Importantly, in adolescents with obesity, acute exercise has been shown not only to counteract these appetitive responses but also, depending on its intensity, to favor a transient anorexigenic effect, leading to a reduction in the adolescents' subsequent food intake (D. Thivel et al. 2016; Thivel et al. 2012).

In adolescents with obesity, a previous study compared the effect of two energy deficits (mean deficit of 200 kcal) induced either by exercise or dietary restriction alone (Thivel et al. 2017). Although both conditions led to a similar subsequent rise in *ad libitum* energy intake, the authors also observed a negative correlation between the individual absolute degree of deficit induced by exercise and the adolescents' food consumption, while a positive correlation was found between the individual deficit induced through dietary restriction and food intake (Thivel et al. 2017). More recently, our research group compared the effect of an acute deficit of 500 kcal induced either by energy restriction alone or by the combination of both exercise and food restriction (mixed-deficit, with a respective deficit of 250 kcal) on short-term energy intake, appetite feelings and food reward in adolescents with obesity (Pélissier et al. 2022). According to our results, neither of the two acute isoenergetic deficits led to subsequent appetitive compensation compared with a control condition without a deficit (Pélissier et al. 2022). Altogether, these results suggest that for a similar induced deficit, physical exercise might limit the subsequent compensatory responses that can be observed in response to dietary restriction, as observed in adults, but that these compensatory responses to exercise *versus* food restriction might depend on the degree of the generated energy deficit in adolescents with obesity (Thivel et al., 2017, 2021).

In that context, the objective of the present work was to compare the appetitive responses (*ad libitum* food intake, appetite sensations and food reward) to similar energy deficits induced by dietary restriction or physical exercise alone in adolescents with obesity. We hypothesized that appetitive compensation would be observed in response to a deficit induced by energy restriction, but not by exercise.

2. Methods

2.1. Participants

Twenty adolescents (aged 12-16 years, Tanner stage 3-5, 9 males) with obesity (as defined by Cole et al. 2000), were recruited from the local Pediatric Obesity Center (Tza Nou, La Bourboule, France). To be included, adolescents had to be free of any medication that could interact with the protocol, could not present any contraindications to physical activity, and had to take part in less than 2 hours of physical activity per week (according to the International Physical Activity Questionnaire – IPAQ). This study was conducted in accordance with the Helsinki declaration and all adolescents and their legal representative(s) received information sheets and signed consent forms as requested by the national ethical authorities (RBHP 2021 JULIAN 2020-A03567-32).

2.2. Experimental design

All the adolescents met with a pediatrician for a preliminary medical inclusion visit to confirm eligibility. Then their body composition was assessed by dual-energy x-ray absorptiometry (DXA), and they performed a maximal aerobic test. The absence of dietary restraint, which has been previously showed to potentially affect post-exercise energy intake (EI) in adolescents with obesity (Miguet et al. 2019), was verified using the Three Factor Eating Questionnaire R-17 (Bryant et al. 2018) and the Dutch Eating Behavior Questionnaire (Brunault et al. 2015). Afterwards, the adolescents randomly completed three 14-hour experimental sessions (separated by at least 7 days): i) control condition (CON); ii) deficit induced by diet only (Def-EI); and iii) deficit induced by exercise only (Def-EX). While the breakfasts and lunches were calibrated and identical during the CON and Def-EX conditions, they were calibrated to generate a 400-kcal dietary deficit on Def-EI. Once during the morning and once during the afternoon, in the Def-EX condition, the adolescents cycled at 65% of their individual VO_{2peak} to create a total exercise-induced deficit of 400 kcal (2x200 kcal). Accordingly, an isoenergetic deficit of 400 kcal was generated in Def-EI and Def-EX. In-between the exercise sessions and the meals, the adolescents were asked not to engage in any physical exercise and mainly performed board games, homework or movie sessions. They were not allowed to consume food or beverages (except water) in-between meals. *Ad libitum* EI was assessed at dinner (07:00 pm), subjective appetite sensations taken at regular intervals throughout the day, and food reward measured immediately before dinner in the three conditions. The Figure 1 presents the design of the study.

2.3. Anthropometric and body measurements

Body weight was measured using a digital scale and height was obtained with a standard wall-mounted stadiometer. Body mass index (BMI) was calculated as body weight (kg) divided by height squared (m^2). Body composition (fat mass and fat-free mass) was assessed by a DXA following standardized procedures (QDR4500A scanner, Hologic, Waltham, MA, USA). These measurements were obtained during the preliminary visit by a trained technician.

2.4. Aerobic capacity

After calibration following manufacturer's recommendation, oxygen consumption (VO2) and carbon dioxide production (VCO2) were measured breath by breath through computer-assisted indirect calorimetry (Quark CPET Cosmed, Rome, Italy) using a Hans Rudolph silicon facemask in the following sequence: (i) for 10 min while comfortably sitting at rest and (ii) during the subsequent cycling exercise. For resting energy expenditure (non-exercise energy expenditure), average VO2 and VCO2 were calculated over the last minute of the resting period where VO2 and VCO2 were stable within 10%. Importantly, resting energy expenditure was measured after a 15-minute calm down period and at least 2 hours after the participants' breakfast. The adolescents did not engage in any exercise or physical activity in-between their breakfast and the measure (this procedure has been previously detailed, see Pelissier et al., 2021). Then, the adolescents completed a maximal incremental cycling test supervised by a specialized medical investigator from the Department of Sport Medicine, Functional and Respiratory Rehabilitation (Clermont-Ferrand University Hospital) (Rowland 1993). The initial power was set at 30 W for the girls and 40 W for the boys for 3 min, following by an increase of 15 W every minute. Cardiac activity, heart rate (HR) and respiratory exchanges (VO_2 and VCO_2) were measured throughout the test. Adolescents were encouraged by the experimenters to perform at maximum effort. Criteria to reaching VO_{2peak} were maximal HR (HR_{max}) > 90% of theoretical HR_{max} (210 – 0.65 × age), respiratory exchange ratio (VCO_2/VO_2) above 1.1 or/and a plateau of VO_2 (Rowland 1996). VO_{2peak} was defined as the mean of VO_2 during the last 30 seconds before the test was stopped.

2.5. Energy expenditure

During CON and Def-EI sessions, adolescents had to keep inactive and were restrained from engaging in any physical activity during the day. During the Def-EX session, between 10:00 a.m. and 11:00 a.m. and between 3:00 p.m. and 5:00 p.m., the adolescents performed a bout of moderate-intensity exercise (65% of VO_{2peak}) on a cycle ergometer. Based on the results of the maximum aerobic test, the duration of exercise was individually determined to create a total gross deficit of 400 kcal and the intensity controlled by HR monitoring (Polar V800).

2.6. Energy intake

During the three experimental sessions, adolescents received their breakfast at 8:00 a.m. and lunch at 12:00 p.m. During the three conditions, a breakfast of 520 kcal was served. Lunch was set at 1230 kcal for CON and Def-EX, in accordance with the nutritional recommendations for their age (total energy content and macronutrient composition) (Pradalié 2003). For Def-EI, a lunch of 830 kcal was served, to induce an energy deficit of 400 kcal. Of note, quantities of lipid, carbohydrate (CHO), and protein were decreased to keep an equivalent proportion of macronutrients similar to the CON and Def-EX conditions. An *ad libitum* dinner (07:00pm) was served in the three sessions using a buffet-type meal. The content of the buffet was determined using a food preference and habits questionnaire completed by participants during the inclusion visit. Top rated items and liked items but not usually consumed were excluded to limit overconsumption and occasional eating. Then the buffet was composed of white ham; turkey, eggs; French been, mashed potatoes, cheese, yoghurt, compote and bred. Meals were prepared in the experimental kitchen and eaten in a dedicated dining room. The experimenters weighed the food items before and after the meal.

This methodology was previously validated and used in previous studies (Thivel et al. 2016). Importantly, the adolescents were not informed about the main purpose of the study and that their EI was weighed. The ANSE nutritional composition table was used to calculate EI and macronutrient intake (quantity and proportion) ("Ciqual Table" Agence Nationale de Sécurité Sanitaire de l'alimentation, de l'Environnement et du travail, ANSES 2020). Total relative EI (REI) and REI at dinner were calculated according to the following formula as previously used in several studies (Masurier et al. 2018; Miguet et al. 2018): REI (kcal) = EI (kcal) – Energy expenditure of the condition (kcal), using the exercise-induced energy expenditure for Def-EX and based on the adolescents non-exercise energy expenditure for Def-EI and CON (for the same duration as the exercise for each adolescent).

2.7. Subjective appetite sensations

Appetite sensations were measured with non-graduated visual analogue scales (VAS) of 150 millimeters (Drapeau et al. 2007). Participants reported their hunger, fullness, desire to eat (DTE), and prospective food consumption (PFC) before, 30 min and 60 min after lunch as well as before and right after dinner. Area under the curve (AUC) for lunch (Lunch+60min AUC) and the day (Total AUC) were calculated using the trapezoid method. The satiety quotient (SQ) for hunger, fullness, DTE, and PFC at lunch and dinner were calculated as follows (Drapeau et al. 2007): SQ (mm/kcal) = [(pre-meal rating (mm)) – (post-meal rating (mm)) / energy content of the meal (kcal)] × 100.

2.8. Food preferences and food reward

Participants completed the Leeds Food Preference Questionnaire 30 min before the dinner. This questionnaire was developed and validated to measure the different components of food reward, liking and wanting (Finlayson, King, et Blundell 2007). Participants were asked to answer questions about images of food divided in four categories: i) savoury and high-fat food; ii) savoury and low-fat food; iii) sweet and high-fat food; and iv) sweet and low-fat food. The measurement of explicit liking and wanting was performed using a VAS (100 millimeters) to answer the following questions: i) "How pleasant would it be to taste this food now?" (explicit liking) and; ii) "How much do you want to eat this food now?" (explicit wanting). Then, a "forced choice" between two food images allowed to measure food preferences (food choice). Frequency and speed of image selection were registered and enabled to measure implicit wanting. We obtained 2 scores, the "fat bias" and the "sweet bias", for each food reward component. The fat bias score was calculated by subtracting low-fat scores from high-fat scores, and the sweet bias score was obtained by subtracting savoury scores from sweet scores. If the score is positive for the fat bias or the sweet bias, there is greater preference for high-fat relative to low-fat food and sweet relative to savoury food, respectively (Oustric et al. 2020). The LFPQ was used in its French version (LFPQ-fr) that has been recently developed and validated following the recommended cultural validation process (Oustric et al., 2020).

2.9. Statistical analysis

Continuous data were expressed as mean ± standard deviation (SD). The assumption of normality was assessed using the Shapiro-Wilk test. The comparisons between conditions (CON, Def-EI, Def-EX) were determined using random-effects models for cross-over designs taking into account the following effects: i) condition, time, sequence, and their interaction as fixed effects; and ii) participant as random-effect to model between and within participants variability. Effect sizes were calculated and interpreted as small (ES: 0.2), medium (ES: 0.5), and large (ES: 0.8, "grossly perceptible and therefore large"). The normality of residuals estimated from these models was analyzed as aforementioned. When appropriate, a logarithmic transformation was applied to access the normality of dependent variables. The statistical analyses were performed using Stata software version 15 (StataCorp, College

Station, US). Statistical tests were two-sided with the type-I error set at 5%, applying a Sidak's type I error correction to take into account multiple comparisons.

3. Results

Of the 20 initially enrolled adolescents, complete data were obtained for 17 of them and the whole data analysis was conducted on these 17 participants. The participants show a mean z-BMI of 2.4 ± 0.3 and a BMI percentile of 98.5 ± 0.8. Their fat-free mass was 60.3 ± 16.5 kg and their fat mass was 36.4 ± 4.6 %. The participants had a mean relative VO_{2peak} of 23.7 ± 5.7 ml/min/kg. The total duration of the two exercise bouts in Def-EX was on average 60 ± 16 min and the target HR was 145 ± 12 beats per min. The resting EE in CON and Def-EI was 136 ± 129 kcal.

3.1. Energy and macronutrient intake

While energy intake at the *ad libitum* dinner was not different between CON (983 ± 277 kcal) and Def-EX (1009 ± 281 kcal), it was greater on Def-EI (1112 ± 265 kcal) compared to the two other sessions (p=0.005 and p=0.025, respectively) (**Figure 2**). Similarly, REI calculated at dinner was higher on Def-EI (976 ± 294 kcal) compared to both CON (846 ± 294 kcal; p=0.005) and Def-EX (609 ± 281 kcal; p<0.001). REI at dinner was also lower on Def-EX compared with CON (p<0.001). **Table 1** displays all the detailed results regarding dinner and total EI and REI.

Regarding macronutrient intake, there was no difference between conditions regarding the percentage of energy ingested from proteins, lipids and carbohydrates at dinner. The absolute consumption of protein was found higher during Def-EI (52.4 ± 9.5 g) compared with both CON (44.9 ± 12.6 g; p=0.001) and Def-EX (47.3 ± 11.8 g, p=0.018), without a difference between CON and Def-EX. Similarly, the absolute consumption of lipids was higher on Def-EI (36.8 ± 8.9 g) compared with both CON (33.8 ± 10.1 g; p=0.002) and Def-EX (35.4 ± 10.1

g, p=0.036), without a difference between CON and Def-EX. All results are presented in **Table 1**.

3.2. Subjective appetite feelings

As detailed in **Table 2**, the SQ for hunger at dinner was higher on Def-EI (11.5 ± 3.7 mm/kcal) compared with CON (9.6 ± 4.4 mm/kcal; p=0.026) and Def-EX (8.3 ± 3.7 mm/kcal; p=0.0002). Similarly, the AUC for hunger 60 min after lunch and total daily AUC for hunger were higher on Def-EI (1069 ± 5152 and 16402 ± 6296 mm/min respectively) compared with both CON (3906 ± 1858 and 8316 ± 3414 mm/min respectively, p=0.0001) and Def-EX (4480 ± 2297 and 9849 ± 3913 mm/min respectively, p=0.0001). Pre-dinner hunger was higher on Def-EI compared with both CON and Def-EX (p<0.0001) (**Figure 3**).

Regarding fullness, no difference was observed for the SQ at dinner between conditions. AUC for fullness 60 min after lunch and total daily AUC for fullness were lower on Def-EI (5338 ± 4698 and 11343 ± 5722 mm/min respectively) compared with both CON (11841 ± 3804 and 18982 ± 5598 mm/min respectively, p=0.0001) and Def-EX (11431 ± 3147 and 18604 ± 4462 mm/min respectively, p=0.0001). Pre-dinner fullness was lower on Def-EI compared with both CON and Def-EX (p<0.0001) (**Figure 3**).

While there was no difference between conditions for the SQ for DTE at dinner, the AUC for DTE 60 min after lunch and total daily AUC for DTE were higher on Def-EI (11486 ± 5102 and 17392 ± 6509 mm/min respectively) compared with both CON (4391 ± 2144 and 8720 ± 3565 mm/min respectively, p=0.0001) and Def-EX (5069 ± 2555 and 10506 ± 4005 mm/min respectively, p=0.0001). Pre-dinner DTE was higher on Def-EI compared with both CON and Def-EX (p<0.0001) (**Figure 3**).

The SQ for PFC at lunch was not different between conditions. The AUC for PFC 60 min after lunch and total daily AUC for PFC were higher on Def-EI (11390 ± 4881 and 17154 ± 6469 mm/min respectively) compared with both CON (4605 ± 2802 and 8895 ± 4546 mm/min respectively, p=0.0001) and Def-EX (4713 ± 2761 and 9728 ± 4603 mm/min respectively, p=0.0001). Pre-dinner PFC was higher on Def-EI compared with both CON and Def-EX (p<0.0001) (**Figure 3**).

3.3. Food reward

Pre-test meal (dinner) food choice and explicit liking were not different between conditions. Regarding explicit wanting sweet bias, it showed a tendency to be higher on Def-EX (19.92 ± 21.43 mm) compared to Def-EI (10.47 ± 18.87 mm; p=0.051) but not CON (12.94 ± 17.20 mm). Implicit wanting sweet bias was found lower on Def-EX (-1.40 ± 52.69) compared with CON (25.21 ± 39.41; p=0.031). **Table 3** detailed on the results for food reward.

4. Discussion

Tailoring acceptable and effective weight loss strategies rests on the elaboration of appropriate interventions aiming at optimizing the induced energy deficit to favor sustainable negative energy balance, while avoiding compensatory behaviors and physiological adaptations trying to maintain or recover body weight. The present study compared the appetitive responses to acute iso-caloric energy deficits induced either by exercise or energy restriction alone, in adolescents with obesity. In line with our initial hypothesis, adolescents with obesity showed an increase of their energy intake and appetite in response to an acute 400-kcal deficit induced by energy restriction but not after an equivalent deficit generated by exercise.

According to our results, while reducing adolescents with obesity's EI by 400 kcal at lunchtime led to an increase of their energy intake at the following meal, the realization over the day of two acute bouts of exercise covering the same energy deficit did not; therefore, avoiding such a short-term compensation. Interestingly, while this short-term higher energy consumption was mainly explained by an increase in lipids and proteins, the relative intake of each macronutrient was not different between conditions. While these results are in line with what has been previously observed in adults, they add to the more limited evidence in adolescents with obesity and tend to confirm the previously suggested hypothesis that exercise alone, depending on the degree of deficit it induces, can counteract the appetitive responses observed after an equivalent acute energy restriction (Thivel et al. 2017, 2021). Indeed, as recently reviewed (Thivel et al. 2021), evidence in adults clearly indicate an increase in the ghrelin concentration accompanied by a reduction of some of the main anorexigenic gastro-peptides (PYY, cholecystokinin and GLP-1) after an acute (from 24 to 72 hours) energy restriction, but not in response to a similar deficit generated by physical exercise (Alajmi et al. 2016; Cameron et al. 2016; King et al. 2011; Thivel et al. 2018). These physiological responses were accompanied by a rise in appetite feelings and decline in fullness after the dietary restriction only, and *in fine* by an increase of the participants' subsequent short-term EI (Alajmi et al. 2016; Cameron et al. 2016; King et al. 2011; Thivel et al. 2018). In adolescents with obesity, while results remain scarce and unclear, similar anti-compensatory effects of acute exercise over energy restriction have been suggested (Pélissier et al. 2022; Thivel et al. 2017, 2021) and seem to be confirmed by the present results.

In line with the observed greater subsequent EI, our results also point out higher daily AUC as well as pre-test meal hunger, PFC and DTE, as well as a lower daily AUC and pre-test meal fullness in response to Def-EI but not Def-EX. Although appetite sensations were not found different in response to a 200-kcal energy deficit induced either by exercise or dietary restriction (Thivel et al. 2017), more recent results indicate that the use of physical exercise as part of a mixed acute deficit (250 kcal deficit induced by exercise + 250 by energy restriction) led to a lower DTE in a similar population (Pélissier et al. 2022). Here again, our results, when compared to previous one obtained in adolescents with obesity, seem to corroborate the hypothesis that the degree of deficit might be of importance to activate the short-term anti-compensatory effects of exercise in this population.

Regarding food reward, we would expect energy deficit-induced compensation to be reflected in greater bias towards high fat/energy foods relative to low fat/energy foods (Finlayson, King, et Blundell 2007). In the present study, although explicit liking and wanting for high fat foods (fat appeal bias) were numerically higher after Def-EI and Def-EX compared to CON, there were no statistically significant differences across conditions. Interestingly, lower implicit wanting for sweets were observed for Def-EX relative to CON which were in line with our appetite and EI results. These results enrich a quite scarce and contradictory literature regarding the effect of acute exercise and energy restriction on food reward in youth with obesity.

In their work, Pélissier *et al.* for instance showed a reduced explicit liking for sweet food in response to a mixed-deficit including an acute exercise compared to a 100% iso-caloric dietary restriction deficit, without any modification of the explicit and implicit wanting (Pélissier et al. 2022). Further studies are definitely needed to better explore and understand these food reward responses to exercise and energy deficit in this population, considering some potential inter-individual differences, such as the adolescents' degree of obesity or the level of cognitive restriction, that could explain such divergent results.

Some limitations have to be considered when interpreting the present results. First, while the aim was to compare the impact of iso-energetic energy deficits, the use of whole room metabolic chambers or of portable indirect calorimeters (during the exercise bouts) would have provided a more accurate control of the adolescents' energy expenditure, which was unfortunately not feasible in this work. The fact that the energy deficit was achieve later during the day on the Def-EX condition compared with the Def-EI condition might also require some attention and should encourage further studies to question the potential impact of the timing of an acute energy deficit on subsequent short-term appetitive responses. Similarly, the fact that the deficit was calculated on a fixed energy intake imposed on the CON and Def-EX conditions and not on the adolescents' usual free-living energy intake (which is highly difficult to assess and usually under-reported and inaccurate) might imply that even during these two conditions, a dietary-induced deficit might exist compared with the participants' habitual intake. Although our analysis proposes a quite complete evaluation of the appetitive mechanisms through the measurement of *ad libitum* EI, appetite feelings and food reward, the addition of physiological measurements of appetite-related peptides would have strengthened our conclusions. Finally, it should also be considered that the eating behaviors of the adolescents might have then been affected by the proximity of their weight loss intervention that was about to start a few days after the evaluations. Importantly, this is here a short-term evaluation of the appetitive responses of adolescents who were all candidate to a weight-loss intervention, and as suggested in the literature in pediatric obesity, different appetitive responses are likely to be observed in response to longer-term deficits induced by multidisciplinary interventions (Miguet et al., 2018). Although this was not the objective of the present work, conducting long-term interventions targeting a specific iso-energetic energy deficit-induced either by physical activity or dietary restriction faces important methodological limitations and difficulties. It must then be emphasized once more that the present conclusions concern short-term adaptations that might be different in response to longer-term energy deficits (Miguet et al. 2019).

Altogether with previously published results, our study suggests that using physical exercise as a way to induce an acute energy deficit seems to optimize the short-term effect on energy balance by mitigating some appetite-related compensatory responses observed after energy restriction, and by reducing the implicit wanting for sweet food, *in fine* avoiding increased subsequent EI. Importantly, although the present work reinforces the hypothesis of a minimal degree of energy deficit necessary to avoid such compensation; further studies are needed in this area.

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Author contributions

DT, LI, VJ, MD, YV: Conceptualization; LP, JS, MB, AB, AF, VJ: Data curation, Investigation; BP, MD, LP: Formal analysis; LI, DT, VJ, KC: Methodology, Project administration; LP, DT: Writing; KC, KB, GF, LI: Review, Editing.

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Legends of figures

Figure 1. Design of the Study. **BF: Breakfast; LFPQ: Leeds Food Preference Questionnaire; CON: Control; Def-EX: Deficit induced by exercise; Def-EI: Deficit induced by energy restriction.**

Figure 2. Dinner and total *Ad Libitum* and Relative Energy intake in response to the control condition (CON), the deficit induced by energy restriction (Def-EI) and the deficit induced by exercise (Def-EX). **EI: Energy Intake; REI: Relative Energy Intake. * $p<0.05$, ** $p<0.01$, *** $p<0.001$.**

Figure 3. Daily subjective appetite sensations and total area under the curve (AUC) for hunger (**A**), fullness (**B**), desire to eat (DTE) (**C**) and prospective food consumption (PFC) (**D**) in response to the control condition (CON), the deficit induced by energy restriction (Def-EI) and the deficit induced by exercise (Def-EX). **BF: breakfast; Lunch+30min: measure 30 minutes after lunch; Lunch+60min: measure 60 minutes after lunch. $p<0.001$.**

Table 1. Absolute, relative energy intake and macronutrient intake in response to the three conditions.

	CON	Def-EI	Def-EX	Mixed model effect ES [Confidence Interval]		
	Mean (SD)	Mean (SD)	Mean (SD)	CON *vs* Def-EI	CON *vs* Def-EX	Def-EI *vs* Def-EX
Energy Intake						
Dinner (kcal)	983 (277)	1112 (265)	1009 (281)	0.005 0.68 [0.20; 1.15]	0.566 0.13 [-0.33; 0.61]	0.025 0.54 [0.07; 1.02]
Total (kcal)	2722 (275)	2388 (264)	2748 (280)	<0.001 -1.76 [-2.23; -1.28]	0.566 0.13 [-0.33; 0.61]	<0.001 -1.90 [-2.37; -1.41]
Relative Energy Intake						
Dinner (kcal)	846 (294)	976 (294)	609 (281)	0.005 0.67 [0.20; 1.15]	<0.001 -1.23 [-1.71; -0.76]	<0.001 1.91 [1.43; 2.39]
Total (kcal)	2585 (292)	2251 (293)	2348 (280)	<0.001 -1.74 [-2.21; -1.26]	<0.001 -1.23 [-1.71; -0.76]	0.037 -0.50 [-0.98; -0.03]
Macronutrients at dinner						
Protein (g)	44.9 (12.6)	52.4 (9.5)	47.3 (11.8)	0.001 0.83 [0.36; 1.31]	0.275 0.26 [-0.21; 0.74]	0.018 0.57 [0.09; 1.04]
Protein (%)	18.5 (3.26)	19.1 (2.2)	19.01 (2.5)	0.215 0.30 [-0.17; 0.77]	0.353 0.22 [-0.25; 0.70]	0.755 0.07 [-0.39; 0.55]
Lipid (g)	33.8 (10.1)	38.6 (8.9)	35.4 (10.1)	0.002 0.74 [0.27; 1.22]	0.324 0.23 [-0.23; 0.71]	0.036 0.50 [0.03; 0.98]
Lipid (%)	31.4 (4.9)	31.6 (4.9)	31.7 (5.4)	0.797 0.06 [-0.41; 0.53]	0.775 0.06 [-0.40; 0.54]	0.977 -0.00 [-0.48; 0.46]
CHO (g)	120.7 (44.1)	134.6 (43.2)	121.5 (41.2)	0.059 0.45 [-0.01; 0.93]	0.915 0.02 [-0.44; 0.50]	0.074 0.43 [-0.04; 0.90]
CHO (%)	48.5 (8.1)	47.6 (6.4)	47.7 (5.9)	0.545 -0.14 [-0.62; 0.32]	0.598 -0.12 [-0.60; 0.34]	0.937 -0.01 [-0.49; 0.45]

CHO: carbohydrates; CON: control condition; Def-EI: deficit induced by energy restriction; Def-EX: deficit induced by exercise; ES: Effect Size.

Table 2. Appetite sensation and satiety quotient results in response to the three conditions.

	CON	Def-EI	Def-EX	Mixed model effect ES [Confidence Interval]		
	Mean (SD)	Mean (SD)	Mean (SD)	CON *vs* Def-EI	CON *vs* Def-EX	Def-EI *vs* Def-EX
Hunger						
SQ Lunch (mm/kcal)	7.3 (3.1)	6.44 (5.1)	8.3 (3.3)	0.494 -0.16 [-0.64; 0.30]	0.414 0.19 [-0.27; 0.67]	0.133 -0.36 [-0.83; 0.11]
SQ Dinner (mm/kcal)	9.6 (4.4)	11.5 (3.7)	8.3 (3.7)	0.026 0.53 [0.06; 1.01]	0.128 -0.36 [-0.84; 0.10]	0.0002 0.90 [0.43; 1.38]
Lunch+60min AUC (mm/min)	3906 (1858)	10639 (5152)	4480 (2297)	0.0001 0.51 [1.03; 1.98]	0.595 0.12 [-0.34; 0.60]	0.0001 1.38 [0.90; 1.85]
Total AUC (mm/min)	8316 (3414)	16402 (6296)	9849 (3913)	0.0001 1.50 [1.02; 1.97]	0.241 0.28 [-0.19; 0.75]	0.0001 1.21 [0.74; 1.69]
Fullness						
SQ Lunch (mm/kcal)	-7.4 (3.5)	-5.0 (6.8)	-8.1 (3.4)	0.097 0.40 [-0.07; 0.87]	0.635 -0.11 [-0.59; 0.36]	0.032 0.51 [0.04; 0.99]
SQ Dinner (mm/kcal)	-10.9 (6.3)	-11.0 (5.7)	-10.9 (4.7)	0.901 -0.03 [-0.50; 0.44]	0.965 -0.01 [-0.48; 0.46]	0.936 -0.19 [-0.49; 0.45]
Lunch+60min AUC (mm/min)	11841 (3804)	5338 (4698)	11431 (3147)	0.0001 -1.37 [-1.85; -0.89]	0.721 -0.08 [-0.56; 0.38]	0.0001 0.28 [-1.76; -0.81]
Total AUC (mm/min)	18982 (5598)	11343 (5722)	18604 (4462)	0.0001 -1.25 [-1.73; -0.78]	0.798 -0.06 [-0.53; 0.41]	0.0001 -1.19 [-1.67;-0.72]
DTE						
SQ Lunch (mm/kcal)	7.4 (2.9)	5.6 (3.6)	8.0 (2.6)	0.080 -0.42 [-0.89; 0.05]	0.524 0.15 [-0.32; 0.62]	0.017 -0.57 [-1.05; -0.10]
SQ Dinner (mm/kcal)	11.0 (7.1)	10.2 (4.2)	10.1 (3.6)	0.621 -0.12 [-0.59; 0.35]	0.591 -0.13 [-0.60; 0.34]	0.966 0.01 [-0.46; 0.48]
Lunch+60min AUC (mm/min)	4391 (2144)	11486 (5102)	5069 (2555)	0.0001 1.66 [1.19; 2.14]	0.511 0.15 [-0.31; 0.63]	0.0001 1.50 [1.03; 1.98]
Total AUC (mm/min)	8720 (3565)	17392 (6509)	10506 (4005)	0.0001 1.60 [1.13; 2.08]	0.173 0.33 [-0.14; 0.80]	0.0001 1.27 [0.79; 1.75]
PFC						
SQ Lunch (mm/kcal)	6.9 (3.5)	4.3 (5.7)	6.8 (4.1)	0.060 -0.45 [-0.93; 0.01]	0.911 -0.02 [-0.50; 0.44]	0.076 -0.42 [-0.92; 0.04]
SQ Dinner (mm/kcal)	9.8 (7.5)	10.3 (3.5)	8.8 (3.6)	0.706 0.09 [-0.38; 0.56]	0.466 -0.17 [-0.65; 0.29]	0.269 0.26 [-0.20; 0.74]
Lunch+60min AUC (mm/min)	4605 (2802)	11390 (4881)	4713 (2761)	0.0001 1.55 [1.07; 2.02]	0.919 0.02 [-0.45; 0.50]	0.0001 1.52 [1.05; 2.00]
Total AUC (mm/min)	8895 (4546)	17154 (6469)	9728 (4603)	0.0001 1.42 [0.94; 1.89]	0.555 0.14 [-0.33; 0.61]	0.0001 1.27 [0.80; 1.75]

AUC: aera under the curve; CON: control condition; Def-EI: deficit induced by energy restriction; Def-EX: deficit induced by exercise; DTE: desire to eat; ES: Effect Size; PFC: prospective food consumption; SQ: satiety quotient.

Table 3. Food reward on the three experimental conditions.

	CON	Def-EI	Def-EX	Mixed model effect ES [Confidence Interval]		
	Mean (SD)	Mean (SD)	Mean (SD)	CON *vs* Def-EI	CON *vs* Def-EX	Def-EI *vs* Def-EX
Food choice						
Fat Bias	8.29 (9.49)	7.76 (8.95)	7.88 (8.72)	0.755 -0.07 [-0.55; 0.39]	0.808 -0.05 [-0.53; 0.41]	0.944 -0.16 [-0.49; 0.45]
Sweet Bias	7.41 (12.37)	7.00 (8.34)	7.23 (12.51)	0.822 -0.05 [-0.52; 0.42]	0.923 -0.02 [-0.49; 0.45]	0.897 -0.03 [-0.50; 0.44]
Explicit liking						
Fat Bias	3.06 (12.16)	9.55 (18.65)	11.13 (14.38)	0.165 0.33 [-0.13; 0.81]	0.085 0.41 [-0.05; 0.89]	0.736 -0.08 [-0.55; 0.39]
Sweet Bias	17.97 (19.85)	12.11 (19.54)	19.61 (20.81)	0.294 -0.25 [-0.73; 0.22]	0.769 0.07 [-0.40; 0.54]	0.178 -0.32 [-0.80; 0.14]
Explicit wanting						
Fat Bias	6.52 (15.73)	12.05 (15.87)	8.11 (13.35)	0.174 0.32 [-0.14; 0.80]	0.696 0.09 [-0.38; 0.57]	0.332 0.23 [-0.24; 0.71]
Sweet Bias	12.94 (17.20)	10.47 (18.87)	19.92 (21.43)	0.612 -0.12 [-0.59; 0.35]	0.150 0.34 [-0.12; 0.82]	0.051 -0.47 [-0.94; 0.003]
Implicit wanting						
Fat Bias	19.12 (33.34)	26.78 (34.79)	16.23 (53.82)	0.487 0.16 [-0.30; 0.64]	0.946 -0.01 [-0.49; 0.45]	0.427 0.19 [-0.28; 0.66]
Sweet Bias	25.21 (39.41)	9.98 (44.79)	-1.40 (52.69)	0.221 -0.29 [-0.77; 0.17]	0.031 -0.52 [-0.99; -0.04]	0.362 0.22 [-0.25; 0.69]

CON: control condition; Def-EI: deficit induced by energy restriction; Def-EX: deficit induced by exercise; ES: Effect Size.