



Higher energy flux may improve short-term appetite control in adolescents with obesity: the NEXT study

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Abstract

Recent evidence suggests better appetite control in states of high-energy flux (HEF) in adults and lean children. Nevertheless, it is unknown whether this extends to youth with obesity. This study compares the effects of low, moderate or HEF on short-term appetitive control in adolescents with obesity. Sixteen adolescents with obesity (12–16 years, Tanner stages 3–5, 11 females) randomly completed three conditions: (i) low-energy flux (LEF); (ii) moderate energy flux (MEF; + 250 kcal) and (iii) HEF (HEF; + 500 kcal). Energy flux was achieved in MEF and HEF through elevated energy intake (EI) and concomitant increase in energy expenditure using cycling exercise (65% $\text{VO}_{2\text{peak}}$). *Ad libitum* EI, macronutrient intake and relative EI were assessed at dinner, subjective appetite sensations taken at regular intervals and food reward measured before dinner. *Ad libitum* EI at dinner was greater in LEF compared with HEF ($P = 0.008$), and relative EI (REI) was higher in LEF compared with MEF ($P = 0.003$) and HEF ($P < 0.001$). The absolute consumption of carbohydrates was lower in LEF compared with MEF ($P = 0.047$) and HEF ($P < 0.001$). Total AUC for hunger and desire to eat was lower in HEF compared with LEF ($P < 0.001$) and MEF ($P = 0.038$). Total AUC for prospective food consumption was lower on HEF compared with LEF ($P = 0.004$). Food choice sweet bias was higher in HEF ($P = 0.005$) compared with LEF. To conclude, increasing energy flux may improve short-term appetite control in adolescents with obesity.

Keywords: Paediatric Obesity: Energy Flux: Exercise: Appetite

The management of paediatric obesity using multidisciplinary interventions combining nutritional strategies, psychological approaches and physical activity programs has previously been shown as effective for weight loss^(1–3). However, the benefits are difficult to maintain over time, leading to frequent weight regain in the following months and years^(4,5). Interestingly, although mainly considered for its effect on increasing energy expenditure, physical activity has been shown to impact both components of energy balance. Some authors have indeed highlighted the importance of physical activity to also indirectly influence energy

intake (EI) and appetite sensations^(6–8). Beneficial appetitive responses to physical activity have been recently highlighted in children and adolescents with obesity⁽⁹⁾. When performed at moderate-to-high intensity, physical exercise has been shown to favour a transient anorexigenic effect, decreasing energy intake without affecting appetite feelings in adolescents with obesity⁽¹⁰⁾. More recently, physical exercise has also been shown to counteract the compensatory appetitive responses that are observed in response to similar energy deficits induced by dietary restrictions, supporting a negative energy balance^(11–13).

Abbreviations: EI, energy intake; HEF, high-energy flux; LEF, low-energy flux; MEF, moderate energy flux; REI, relative EI; GLP-1, glucagon-like peptide-1; BMI, body mass index; DXA, dual-energy X-ray absorptiometry; HR, heart rate.

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Although the available literature has mainly explored the effect of acute exercise alone or in comparison to similar energy deficits induced by dietary restriction, Hägele *et al.* recently examined appetitive responses to different levels of exercise energy expenditure matched with raised levels of dietary energy intake, producing different levels of 'energy flux'⁽¹⁴⁾. Briefly, energy flux in this context corresponds to the total volume of energy consumed through energy intake and expenditure, independent of energy balance status (i.e. deficit, maintenance or surplus of energy). Thus, a high-energy flux (HEF) is determined by a high level of EI where the level of energy expenditure is also high⁽¹⁵⁾. In healthy adults, Hägele *et al.* showed that HEF was associated with lower subsequent *ad libitum* intake, an increase in Glucagon-like peptide-1 (GLP-1) concentrations and a decrease in acylated ghrelin, insulin concentrations, hunger and desire to eat⁽¹⁴⁾. A HEF has also been shown to induce a greater increase in post-exercise and 24 h fat oxidation^(16,17). In a pilot study, Paris *et al.* (2016) showed that following weight loss, a higher energy flux was associated with a higher basal metabolic rate and fat oxidation, lower perception of hunger and greater satiety in adults with obesity, compared with a similar energy balance achieved through a lower energy flux⁽¹⁸⁾. The authors then suggested that a higher energy flux might help in limiting the metabolic adaptations and in reducing hedonic-driven food intake following weight loss, which are often associated with weight regain. To date, only one study has investigated the effects of the level of energy flux in adolescents with normal weight. The authors reported that a HEF may be more effective in reducing body fat gain over a 3-year follow-up period, in part because of its association with higher resting metabolic rate⁽¹⁹⁾. While all these studies have been conducted in adults or lean adolescents, it seems important to examine the potential role of energy flux on appetite regulation in paediatric obesity in order to inform weight management interventions.

In that context, the aim of this study was to compare the short-term effects of low, moderate or high-energy flux on food and macronutrient intake, appetite sensations and food reward in adolescents with obesity. We hypothesised that a HEF would be associated with lower *ad libitum* food intake, lower appetite sensations and lower liking and wanting for high fat foods compared with a low-energy flux (LEF).

Methods

Participants

Sixteen adolescents (aged 12–16 years, Tanner stages 3–5, 5 males) with obesity (as defined by Cole *et al.* 2000)⁽²⁰⁾ were included in the study and recruited from the Local Pediatric Obesity Center (Tza Nou, La Bourboule, France). The inclusion criteria to participate in this study were (1) adolescents aged between 12 and 16 years; (2) to have obesity based on sex- and age-specific World Obesity Federation cut-off points (Cole *et al.* 2000, 2012); (3) to be free of any medication that could interact with the results of the study; (5) not to be involved in any energetic restriction or weight loss program through physical activity at the time of inclusion or during the last 6 months; (7) to be free of any alcohol or tobacco use and (8) to not present any

contraindications to physical activity and) to practice less than 2 h of physical activity per week according to the International Physical Activity Questionnaire. Parents or legal guardians were informed of the purpose of the study, and written informed parental and child consent was obtained. The NEXT project was approved by the relevant Human Research Ethics Authority (RBHP 2021 BOIRIE 2-2021-A02867-34) and registered as a clinical trial (NCT05365685).

Study design

After an inclusion visit with a paediatrician to ensure the eligibility of the adolescents to complete the whole study, their resting energy expenditure was evaluated and all of them performed a maximal aerobic test on a bicycle ergometer to determine their peak oxygen consumption ($\text{VO}_{2\text{peak}}$). Their body composition was assessed by dual-energy X-ray absorptiometry. Afterwards, the adolescents completed three 14-h experimental sessions (separated by at least 7 d) in a randomised crossover design: (i) low-energy flux (LEF); (ii) moderate energy flux (MEF); and (iii) high-energy flux (HEF). During the LEF session, the adolescents did not perform any physical activity and their breakfast and lunch were calibrated at respectively 500 and 700 kcal. In MEF and HEF sessions, the energy intake of breakfast was identical and calibrated at 500 kcal (as in the LEF session) and lunches were increased by additional 250 (MEF) or 500 kcal (HEF) compared with the LEF condition. In MEF and HEF sessions, adolescents performed a moderate intensity cycling exercise (65 % of their individual $\text{VO}_{2\text{peak}}$) during the afternoon, inducing an energy expenditure of either 250 (MEF) or 500 kcal (HEF), and whose duration was individually calibrated. Regardless of the conditions, adolescents were not allowed to consume food or beverages (except water) in-between meals. *Ad libitum* food intake was measured at dinner (07.00) as the primary outcome. Subjective appetite sensations taken at regular time intervals throughout the day and food reward measured before and after lunch and before dinner in all three conditions (as secondary outcomes). The study design is presented in Fig. 1.

Anthropometric and body measurements

Body weight was measured using a digital scale, and height was obtained using a standard wall-mounted stadiometer. Body mass index (BMI) was calculated as weight (kg) divided by height squared (m^2). Body composition (fat mass, lean mass and bone mineral mass) was assessed by dual-energy X-ray absorptiometry (DXA) following standardised procedures (QDR-4500A, Hologic, Inc.).

Resting and maximal aerobic capacity

Resting and maximal aerobic capacity were assessed in the Department of Sport Medicine, Functional and Respiratory Rehabilitation (Clermont-Ferrand University Hospital). The adolescents were first asked to remain quiet at rest in a supine or semi-supine position for 20 min while wearing a face mask measuring their gas exchanges by indirect calorimetry. The last 10 min of this 20 min period were used to calculate their resting



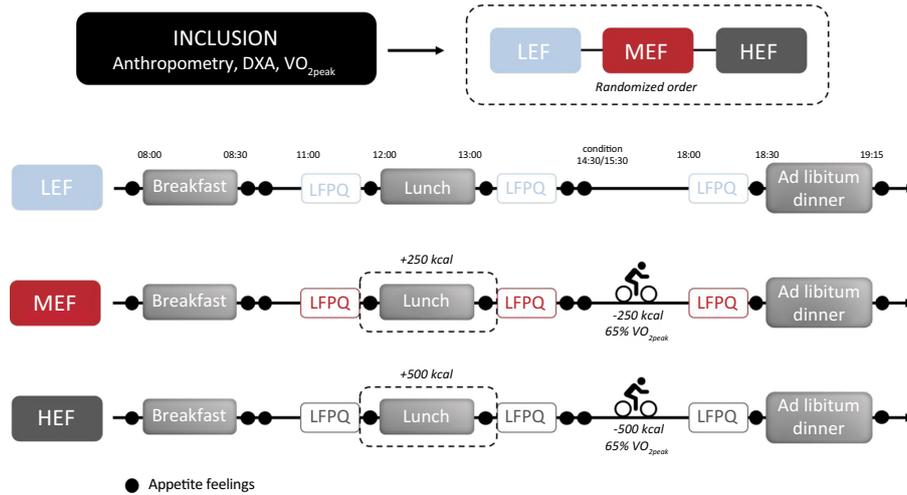


Fig. 1. Design of the study. HEF, high-energy flux; LEF, low-energy flux; LFPQ, Leeds Food Preference Questionnaire; MEF, moderate energy flux.

energy expenditure. Then, their maximal aerobic capacities were determined during a maximal incremental cycling test supervised by a specialised medical investigator⁽²¹⁾. The test started with 3 min at an initial power of 30 watts for girls and 40 watts for boys, followed by an increment of 15 watts per minute. During this maximal aerobic capacity test, electrocardiogram, heart rate, blood pressure and gas exchanges (oxygen consumption (VO_2), carbon dioxide production (VCO_2) and ventilation (VE)) were continuously assessed (BreezeSuite Software, Medgraphics Cardiorespiratory Diagnostics). Adolescents were encouraged by the experimenters to perform their best and maximum effort. The criteria for cessation of exercise were those determined by Rowland (1996): (i) to reach more than 90% of theoretical maximal heart rate ($210 - 0.65 \times \text{age}$); (ii) respiratory exchange ratio (VCO_2/VO_2) above 1.1 or (iii) a plateau of VO_2 . The VO_{2peak} was defined as the highest VO_2 value averaged over 30 s. For this test, the adolescents had not performed any physical activity in-between breakfast and the measure (this procedure has been previously detailed by Fillon *et al.* 2023; Pélissier *et al.* 2022).

Energy expenditure

During MEF and HEF sessions, adolescents performed a single bout of moderate intensity cycling exercise (65% of their individual VO_{2peak}). The heart rate corresponding to 65% of their individual VO_{2peak} from the maximal exercise test was determined and used to regulate the intensity of the exercise bout. Based on the results of the maximal aerobic capacity test, the duration was individually calculated to generate a total energy expenditure of 250 (MEF) or 500 kcal (HEF), maintaining a continuous intensity using a heart rate monitor (Polar V800). During LEF session, adolescents had to remain inactive and could not engage in any physical activity during the day.

Energy intake

During the three experimental sessions, adolescents received their breakfast at 08.00 a.m. and lunch at 12.00 p.m. In all three conditions, a 500 kcal breakfast was served in accordance with

the nutritional recommendations for their age (total energy content and macronutrient composition)⁽²²⁾. Lunch was set at 750 kcal for LEF, 900 kcal for MEF and 1200 kcal for HEF, in order to increase the energy intake of 250 (in MEF) or 500 kcal (in HEF). To note, the quantity of carbohydrates was increased to keep an equivalent proportion of macronutrients similar in all the sessions. The distribution of macronutrients for each condition is shown in Table 1 in Supplementary Materials. Dinner was served as an *ad libitum* buffet, and food consumption was measured by members of the investigation team who weighed each food item before and after the meal (this methodology has been previously used and validated in other studies)^(11–13,23). The components of the meals were chosen on the basis of food preference and dietary habits questionnaires filled out during the inclusion visit. Foods indicated as 'preferred' by the participants were not offered during these sessions in order to avoid any influence of their palatability on the participants' consumption. Similarly, foods that were indicated as liked but not regularly consumed were not presented so as not to create occasional consumption. Considering the answers from all the adolescents, a common buffet was elaborated and composed of white ham; turkey; eggs; French bean, mashed potatoes, cheese, yoghurt, compote, and bread. Importantly, the adolescents were not informed about the main purpose of the study and that their energy intake (EI) was assessed. The ANSES (Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail) nutritional composition was used to calculate energy and macronutrients intake (quantity and proportion) (Ciqual Table, ANSES 2020). Relative EI (REI) at dinner was calculated according to the following formula used in several previous studies^(12,13,24,25): $REI \text{ (kcal)} = EI \text{ (kcal)} - EE \text{ (kcal)}$. The energy expenditures induced by the respective exercises were used to calculate REI during MEF and HEF sessions. Regarding the LEF session, resting energy expenditure assessed before the maximal aerobic test was used to estimate REI according to the MEF and HEF exercise durations. Since the exercises did not have the same duration on MEF and HEF, two REI were calculated for LEF: REI_1 (using the exercise duration of MEF) and REI_2 (using the exercise duration of HEF).

Appetite sensations

Appetite sensations were taken at regular intervals throughout the experimental days (before, immediately after and +30 min after breakfast; before, immediately after, +30 min and +60 min after lunch as well and before and immediately after dinner) using visual analogue scales (VAS) of 150 mm^(26,27). Adolescents reported their sensations of hunger, satiety, desire to eat (DTE) and prospective food consumption (PFC) with 0 corresponding to 'Not at all' and 150 to 'A lot'. AUCs were calculated for lunch (Lunch+60 min AUC) and the day (total AUC) using the trapezoid method. The satiety quotient (SQ) for hunger, satiety, DTE and PFC were calculated as follows: $SQ (\text{mm/kcal}) = ((\text{pre-meal rating (mm)}) - (\text{post-meal rating (mm)})) / \text{energy content of the meal (kcal)} \times 100^{(27)}$.

Food reward and hedonic responses

Adolescents completed the Leeds Food Preference Questionnaire (LFPQ) 30 min before lunch, just after lunch and 30 min before dinner. This questionnaire was developed to measure different components of food reward, liking, and wanting⁽²⁸⁾. Adolescents were asked to answer a series of questions about their food preferences (food choice) by selecting, in a 10-min computer exercise, the foods they preferred from a number of pictorial items. In the same way, they were asked during this exercise to estimate, using a 100 mm visual analogue scale, how much they would like to eat certain foods divided into 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 two questions used were: (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?' 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 by subtracting savoury scores from sweet scores. If the score was positive for the fat or the sweet bias, there is a preference for high-fat relative to low-fat food and sweet relative to savoury food, respectively⁽²⁹⁾. A French version of the LFPQ (LFPQ-fr), recently developed and validated according to the recommended cultural validation process⁽²⁹⁾, was used in this work (Thivel *et al.* submitted).

Statistical analysis

Randomization was performed using a randomization list predetermined by the study biostatistician (BP) using permuted blocks and remained confidential until after database lock. Sample size was estimated according to (i) the CONSORT 2010 statement, extension to randomized pilot and feasibility trials and (ii) Cohen's recommendations, which define effect-size bounds as small (ES: 0.2), medium (ES: 0.5) and large (ES: 0.8, 'grossly perceptible and therefore large') and (iii) previous works reported in literature^(9,11,24,30-33). As reported in prespecified sample size estimation section of our protocol, for a two-sided type I error at 0.017 (correction due to multiple comparisons

between conditions), at least 14 patients were needed in order to highlight an effect size greater than 1 (i.e. minimal differences between conditions equals one standard-deviation), especially for energy Intake, for an 80% statistical power and an intra-individual correlation coefficient fixed at 0.5. It was proposed to include 18 participants to take into account unavailable data (such as lost to follow-up, etc.). Continuous data were expressed as mean \pm standard deviation (SD). The assumption of normality was assessed using the Shapiro-Wilk test. The comparisons between conditions were carried out using random-effects models for cross-over designs considering the following effects: i) condition, period, sequence, and their interaction as fixed effects and ii) participant as random-effect to model between and within subject 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 (Stata Corp). Statistical tests were two-sided with the type-I error set at 5%, applying a Sidak's type I error correction to consider multiple comparisons.

Results

The descriptive characteristics of the study sample are presented in Table 1 for 14 (4 males) of the 16 adolescents initially enrolled because 2 of them did not eat the entire calibrated lunch of the first experimental day which affects the total EI and therefore the energy flux over the day. The whole data analysis was conducted on these 14 participants. They had a mean age of 12.6 ± 1.0 years, an average BMI of $39.9 \pm 9.2 \text{ kg/m}^2$ and a BMI percentile above the 97th percentile (98.9 ± 0.4). Regarding their body composition, their fat-free mass was $64.6 \pm 18.8 \text{ kg}$, and their fat mass was $38.8 \pm 4.2 \%$. The adolescents had a mean relative $\text{VO}_{2\text{peak}}$ of $20.2 \pm 5.0 \text{ ml/min/kg}$. The duration of the exercise bout was on average $37 \pm 7 \text{ min}$ and $73 \pm 14 \text{ min}$ in respectively MEF and HEF condition, and the targeted heart rate (HR) was $145 \pm 11 \text{ beats per minute}$.

Table 1. Descriptive characteristics of the adolescents (*n* 14)

	Mean	SD
Anthropometric characteristics		
Age (years old)	12.6	1.0
Weight (kg)	109.3	32.6
Height (m)	1.6	0.1
BMI (kg/m^2)	39.9	9.2
BMI percentile	98.9	0.4
FFM (kg)	64.6	18.8
FM (%)	38.8	4.2
Relative $\text{VO}_{2\text{peak}}$ (ml/min)	20.2	5.0
Exercise characteristics		
Exercise duration (min)		
MEF condition	37	7
HEF condition	73	14
Target HR (bpm)	145	11

BMI, body mass index; FM, fat mass; FFM, fat-free mass; HEF, high-energy flux; HR, heart rate; LEF, low-energy flux; MEF, moderate-energy flux; $\text{VO}_{2\text{peak}}$, peak oxygen consumption.

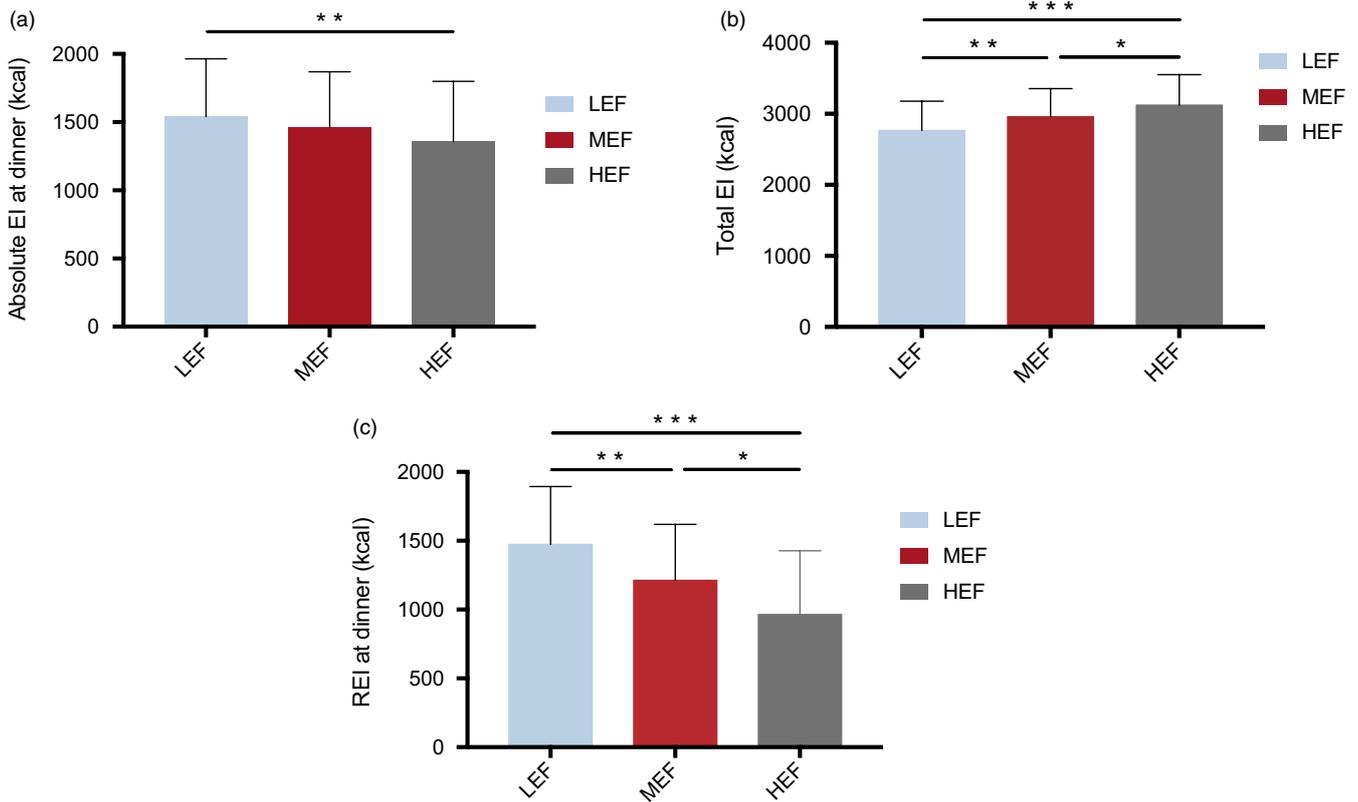


Fig. 2. Absolute and relative dinner and total *ad libitum* energy intake in response to the three conditions. EI, energy intake; REI, relative energy intake.

Energy and macronutrient intake

Figure 2 displays all the detailed results regarding dinner and REI. Results showed significantly higher *ad libitum* EI at dinner in LEF (1541 ± 423 kcal) compared with HEF (1357 ± 442 kcal; $P=0.008$; ES: -0.71 (-1.23, -0.19)) while no difference was found in MEF (1463 ± 407 kcal) compared with the two other sessions (Fig. 2). REI calculated at dinner was higher in LEF (1475 ± 420 kcal for REI_1 and 1408 ± 417 for REI_2) compared with MEF (1213 ± 407 kcal; $P=0.003$; ES: -0.80 (-1.33, -0.28) and $P=0.023$; ES: -0.61 (-1.13, -0.08) respectively) and HEF (964 ± 463 kcal; $P<0.001$; ES: -1.42 (-1.94, -0.80) and $P<0.001$; ES: -1.23 (-1.76, -0.871) respectively). Also, we found a significant difference in REI at dinner between MEF and HEF ($P=0.019$; ES: 0.62 (0.10, 1.15)). Total daily EI was significantly higher in HEF (3122 ± 430 kcal) compared to LEF (2766 ± 413 kcal; $P<0.001$; ES: 1.44 (0.91, 1.96)) and MEF (2959 ± 394 kcal; $P=0.011$; ES: -0.68 (-1.20, -0.15)) and in MEF compared to LEF ($P=0.004$; ES: 0.76 (0.24, 1.28)). Regarding macronutrient intake, there was no significant difference in dinner macronutrient distribution between condition (Table 2). The absolute consumption of carbohydrates at dinner was found higher during MEF and HEF compared with LEF ($P=0.047$; ES: -0.53 (-1.05, 0.006) and $P<0.001$; ES: -0.93 (-1.46, 0.41) respectively) while no other significant difference was obtained. Differences in total daily energy intake difference from the LEF condition as a percentage of the increased energy expenditure induced by exercise calculated for each subject. These

differences are presented in Figure S1 that shows an important inter-individual variability. When considering the means for the whole sample, a higher but not significant percentage difference was observed for the MEF compared to the HEF condition.

Subjective appetite feelings

As shown in Fig. 3 total AUC for hunger and DTE were lower in HEF (10 488 ± 4226 and 11 693 ± 4493 mm² respectively) compared with both LEF (13 924 ± 5849 and 16 461 ± 5601 mm², $P<0.001$ respectively) and MEF condition (12 837 ± 4395 and 15 805 ± 5775 mm², $P=0.038$ and $P<0.001$ respectively). Similar results were obtained for the PFC total AUC with a significant difference between HEF (12 119 ± 5252 mm²) and LEF condition (15 580 ± 5613 mm², $P=0.004$). For hunger, DTE and PFC, lunch+60 min AUC were significantly lower in HEF (5597 ± 3345, 6462 ± 3287 and 6617 ± 3980 mm² respectively) than in LEF (8696 ± 4913, 10 719 ± 4815, and 9710 ± 4686 mm² respectively, $P<0.001$ for all), and MEF sessions (7418 ± 3726, 9416 ± 4373 and 8066 ± 4356 mm² respectively, $P=0.039$; $P<0.001$, and $P=0.046$ respectively). Considering lunch+60 min AUC for fullness, there was also a significant difference between HEF (7068 ± 4527 mm²) and LEF (4697 ± 3385 mm², $P=0.021$). Regarding hunger, fullness, and PFC, no difference was observed for the SQ at lunch and dinner between conditions. Dinner SQ for DTE was significantly lower in HEF than in LEF ($P=0.028$).

Table 2. Macronutrient intake in response to the three conditions

Macronutrients at dinner	LEF		MEF		HEF		LEF v. MEF			LEF v. HEF			MEF v. HEF		
	Mean	SD	Mean	SD	Mean	SD	Mixed model effect	ES	CI	Mixed model effect	ES	Confidence interval	Mixed model effect	ES	Confidence interval
Protein (g)	76.0	25.3	74.5	31.0	67.3	25.2	0.796	-0.07	-0.59, 0.45	0.162	-0.38	-0.90, 0.15	0.254	0.30	-0.22, 0.83
Protein (%)	19.7	4.3	19.9	4.4	19.6	3.9	0.813	0.06	-0.46, 0.59	0.926	0.02	-0.50, 0.55	0.886	0.04	-0.49, 0.56
Lipid (g)	51.5	13.6	51.1	12.1	48.4	15.6	0.898	-0.03	-0.56, 0.49	0.355	-0.25	-0.77, 0.28	0.426	0.21	-0.31, -0.74
Lipid (%)	30.9	6.0	32.6	8.0	32.7	6.1	0.150	0.39	-0.14, 0.91	0.145	0.39	-0.13, 0.91	0.987	-0.004	-0.53, 0.52
CHO (g)	188.5	62.7	172.7	60.5	159.9	61.8	0.047	-0.53	-1.05, -0.006	< 0.001	-0.93	-1.46, 0.41	0.131	0.40	-0.12, 0.93
CHO (%)	48.4	6.5	46.7	9.2	46.7	7.7	0.151	-0.38	-0.91, 0.14	0.130	-0.41	-0.93, 0.12	0.936	0.02	-0.50, 0.55

CHO, carbohydrates; ES, effect size; FFM, fat mass; FFM, fat-free mass; HEF, high-energy flux; HR, heart rate; LEF, low-energy flux; MEF, moderate energy flux.

Food reward

As detailed in Table 3, the components of food reward were not significantly different between conditions except for food choice where sweet bias was higher in HEF (7.6 ± 9.5 mm) compared to LEF (2.3 ± 12.7 mm; P = 0.005).

Discussion

In youth with overweight and obesity, there is a clear need to better understand the regulation of energy balance and especially the related behavioral and physiological compensatory mechanisms that appear after weight loss that favor weight regain. To our knowledge, this study is the first to explore the effect of energy flux on appetite and food intake in adolescent with overweight/obesity, which aimed to compare the short-term effects of different levels of energy flux (low, moderate, or high) on subsequent food and macronutrient intake, appetite sensations and food reward in this population. According to our hypotheses, our results suggest a benefit of higher energy flux via lower absolute and relative energy intake during an *ad libitum* test meal as well as lower subjective hunger, desire to eat and prospective food consumption over the day. We also found no differences in liking or wanting for high fat foods, but a higher bias for sweet foods was observed in the HEF condition. Overall, these findings provide preliminary evidence that comports with previously published studies performed in normal weight adolescents and adults that may suggest better regulation of appetite with higher energy flux, but more comprehensive, longer term studies are needed to substantiate the relationship between energy flux and appetite control^(14,19).

According to our results, a higher energy flux resulted in lower energy intake at a subsequent *ad libitum* test meal in adolescents with obesity, compared to low and medium ones. These results are in line with previous observations in similar studies conducted in lean adults^(14,17). In their work with healthy adults, Hägele and colleagues for instance observed a lower *ad libitum* energy intake after 3 experimental days spent at higher energy flux compared to medium or low flux. Interestingly, in this last work the authors observed this lower energy intake independently of the nature of the individual's energy balance (neutral, +25 % or -25 % EB)⁽¹⁴⁾. Moreover, while the increase in energy expenditure induced on MEF compared with LEF was similar to what has been previously suggested as insufficient to impact appetite control (250 kcal)⁽¹²⁾, the findings observed during the HEF condition (500 kcal) and subsequent food intake reduction reinforce the observations in previous works that suggest the need for a minimal degree of energy deficit to positively affect appetite and food intake in youth suffering obesity⁽¹¹⁾. Overall, these results provide tentative to support for the importance of physical exercise in the management of short-term energy balance rather than emphasizing reduced food consumption which remains difficult in the context of an obesogenic food environment^(34,35), via induced energy expenditure, positive cardio-respiratory and muscular effects⁽³⁶⁾, and a potential benefit in regulation of food intake⁽¹⁰⁾. Indeed, a low energy flux seems difficult to sustain in the long term for most people because, as explained by Swift *et al.*⁽³⁷⁾, the high

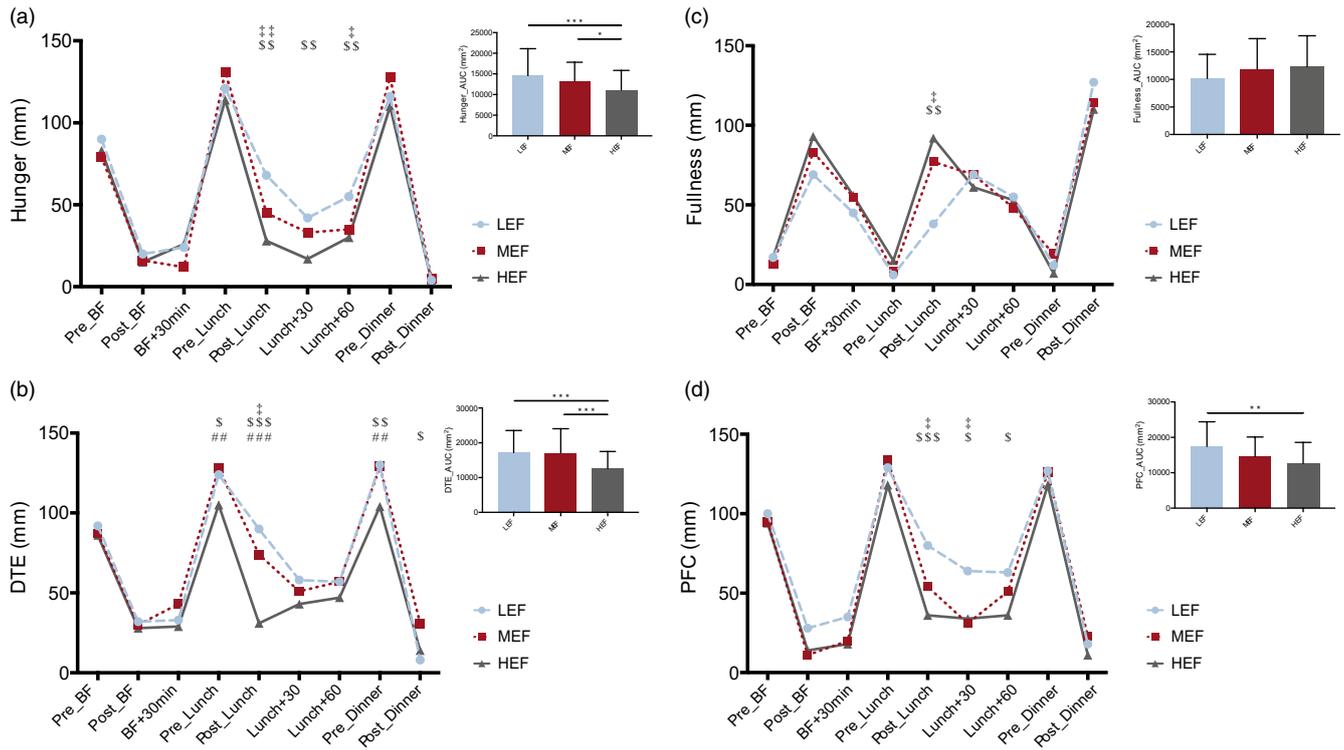


Fig. 3. Daily subjective appetite sensations and total area under the curve (AUC) for hunger, desire to eat (DTE), fullness and prospective food consumption (PFC) in response to the three conditions. (†), LEF vs. MEF; (#), MEF vs. HEF; (\$), LEF vs. HEF; (†, #, \$), $P < 0.05$; (††, ##, \$\$), $P < 0.01$; (†††, ###, \$\$\$), $P < 0.001$.

food availability environment results in high energy intake, which is the principal driver of the return to a HEF. Altogether, these results may suggest a potential benefit of emphasizing physical activity in the management of pediatric obesity through a more efficient coupling of energy intake and expenditure above a certain threshold of energy flux conducive to body weight maintenance⁽³⁸⁾. However, longer term studies are needed to attribute the effects on energy intake to the energy flux with more confidence, given the evidence that metabolic adaptations occur over time frames longer than that used in this study.

Additionally, we observed lower overall daily sensations of hunger, DTE, and PFC as well as a lower pre-test meal DTE during the HEF condition relative to both LEF and MEF, suggesting adaptations in appetite control as a potential mechanism for the aforementioned effects on energy intake.

These findings are also in line with previous studies showing decreased hunger and DTE during HEF sessions in adults with normal weight⁽¹⁴⁾. Our results could be explained by the fact that exercise has a suppressant effect on appetite that may lead to greater meal-induced satiety and better appetite regulation^(6,15,39,40). Furthermore, based on the findings of Paris *et al.*⁽¹⁸⁾ weight-reduced adults with obesity reported a decrease in subjective hunger ratings and an increase in satiety following four experimental days of HEF compared to the four days of low flux. Since a high perceived hunger sensation has been shown to predict greater weight regain⁽⁴¹⁾, the reduction thereof could contribute to limiting or preventing weight regain that is typically observed after weight loss interventions⁽⁴²⁾. Altogether these results indicate, in line with previous studies^(34,43) that exercise,

even when combined with higher energy intake, may improve the short-term regulation of appetite in adolescents with obesity.

In line with our expectations, we observed that lower energy flux was associated with a greater preference for high-fat/energy foods over low-fat/energy food stimuli. Low energy flux has been postulated as a metabolic state associated with lower appetite control where there may be a greater susceptibility to hedonic inputs from foods and reward driven eating, in contrast to HEF where satiety signaling could be improved and appetite is more tightly regulated⁽⁴⁴⁾. Contrary to expectations however, our results showed a significantly higher food choice sweet bias after HEF compared to LEF while there were no other statistical differences between conditions in bias for sweet foods. In addition, there was a dissociation between wanting and liking with an increase in wanting but a decrease in liking, following energy intake. Overall, these observed trends may indicate that, although both components are important, the measurement of liking seems to be even more important for understanding the energetic adaptations that occur following modulation of energy flux. The short-term nature of the study could partly explain these results, suggesting that liking may be more likely to change in the short term compared to wanting, which is also linked to increase in choice, as this is part of the implicit wanting metric. In this sense, a longer-term intervention and observation period might be better suited to highlight changes in wanting. Future studies are needed to further explore changes in food reward responses as a function of energy flux, with particular consideration of, as indicated by Fillon *et al.*⁽¹³⁾ potentially influential factors such as the degree of adiposity and intervention duration.

Table 3. Food reward on the three experimental conditions

	LEF		MEF		HEF		LEF vs. MEF			LEF vs. HEF			MEF vs. HEF		
	Mean	SD	Mean	SD	Mean	SD	Mixed model effect	ES	CI	Mixed model effect	ES	Confidence interval	Mixed model effect	ES	Confidence interval
Implicit wanting	25.4	18.5	35.3	30.9	27.0	15.8	0.133	0.40	-0.12, 0.92	0.739	0.09	-0.43, 0.61	0.252	0.31	-0.22, 0.83
Fat bias	6.9	38.9	8.9	28.8	17.1	24.2	0.848	0.05	-0.47, 0.58	0.203	0.34	-0.18, 0.86	0.291	-0.28	-0.81, 0.24
Food choice															
Fat bias	11.3	8.4	10.6	8.8	11.6	6.3	0.513	-0.17	-0.70, 0.35	0.919	0.03	-0.50, 0.55	0.450	-0.20	-0.73, 0.33
Sweet bias	2.3	12.7	5.4	10.4	7.6	9.5	0.078	0.47	-0.05, 0.99	0.005	0.76	0.23, 1.28	0.285	-0.29	-0.81, 0.24
Explicit liking															
Fat bias	11.9	15.2	13.6	16.3	11.8	14.3	0.682	0.11	-0.42, 0.63	0.902	-0.03	-0.56, 0.49	0.595	0.14	-0.38, 0.67
Sweet bias	11.3	19.0	12.5	26.03	7.1	16.4	0.754	0.08	-0.44, 0.61	0.444	-0.20	-0.73, 0.32	0.281	0.29	-0.24, 0.81
Explicit wanting															
Fat bias	16.0	14.1	14.9	17.2	13.8	16.8	0.742	-0.09	-0.55, 0.40	0.514	-0.17	-0.70, 0.35	0.747	0.09	-0.44, 0.61
Sweet bias	11.0	21.5	13.3	20.9	7.3	14.0	0.640	0.12	-0.40, 0.65	0.521	-0.17	-0.70, 0.35	0.268	0.30	-0.23, 0.82

ES, effect size; HEF, high-energy flux; LEF, low-energy flux; MEF, moderate energy flux.

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The results of this study must be interpreted in light of some limitations. First, although based on previously measured resting metabolic rate and maximal aerobic capacities, the energy expenditure induced during the experimental session was estimated using heart rate records, while the use of indirect calorimeters (and ideally metabolic chambers) would have been more accurate to obtain more precise results. Second, the present work compared different levels of energy flux generated through the course of a single day, with appetitive responses mainly assessed on the basis of a single subsequent meal, thus longer term research is needed to evaluate the effects of energy flux on appetitive responses with more confidence. It could also be interesting to conduct these future studies particularly after a weight loss period to test the efficacy of exercise-induced HEF as a weight regain prevention tool. Indeed, some studies have suggested that the appetitive responses to exercise may occur over few days⁽⁴⁴⁾. However, research has previously demonstrated transient metabolic and appetitive adaptations can occur after acute exercise, thus it is feasible that higher energy flux may also have similar acute and short-term effects⁽⁴⁵⁾. Finally, our study lacked information regarding the usual free-living daily energy balance and energy flux of the adolescents, thus it is not possible to compare the energy intake volumes observed here to their usual dietary habits. It is important to note that it remains extremely and resource intensive to properly track daily free-living energetic and nutritional behaviors in addition to the high inter-individual variability in appetitive responses to exercise shown in Supplementary Fig. 1. However, future research would undoubtedly benefit from a longer time frame and multiple assessments to mitigate such a limitation.

Conclusion

The findings of the present study suggest that a higher energy flux might lower *ad libitum* energy intake at a subsequent test meal in adolescents with obesity via lower total daily hunger, DTE, PFC and preference for high-fat foods, indicative of enhanced appetite control. Increasing energy expenditure through exercise may be more effective in improving short-term appetite control than energetic restriction alone, often considered the main target in the management of obesity. As recently reviewed by Bosy-Westphal *et al.*⁽¹⁵⁾, unlike exercise, small increase in energy flux induced by short sleep duration or increased mental work can lead to an increase in energy intake and thus to a deregulation of the energy balance. Future studies comparing different levels of energy flux over a longer time frame are needed to better understand and characterise the appetitive responses to energy balance manipulations that may inform design of interventions that improve sustainable weight loss interventions and fight the childhood obesity pandemic.

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Supplementary material

For supplementary material/s referred to in this article, please visit <https://doi.org/10.1017/S0007114523001824>

References

- Dâmaso AR, De Piano A, Campos RM, *et al.* (2013) Multidisciplinary approach to the treatment of obese adolescents: effects on cardiovascular risk factors, inflammatory profile, and Neuroendocrine Regulation of Energy Balance. *Int J Endocrinol* **2013**, Article ID: 541032, 10 pages.
- Freitas CRM, Gunnarsdottir T, Fidelix YL, *et al.* (2017) Effects of a psychological intervention on the quality of life of obese adolescents under a multidisciplinary treatment. *J Pediatr (Rio J)* **93**, 185–191.
- Caranti DA, Inoue DS & Lira FS (2022) Editorial: challenges for obesity in the 21st century: psychology, nutrition, modern lifestyle behavior and neuroendocrine responses. *Front Nutr* **9**, 1–3.
- Rank M, Wilks DC, Foley L, *et al.* (2014) Health-related quality of life and physical activity in children and adolescents 2 years after an inpatient weight-loss program. *J Pediatr* **165**, 732–737.e2.
- Reinehr T, Widhalm K, l'Allemand D, *et al.* (2009) Two-year follow-up in 21 784 overweight children and adolescents with lifestyle intervention. *Obesity* **17**, 1196–1199.
- Blundell JE, Gibbons C, Caudwell P, *et al.* (2015) Appetite control and energy balance: impact of exercise. *Obes Rev* **16**, 67–76.
- Cameron JD, Goldfield GS, Riou MÈ, *et al.* (2016) Energy depletion by diet or aerobic exercise alone: impact of energy deficit modality on appetite parameters. *Am J Clin Nutr* **103**, 1008–1016.
- Casanova N, Beaulieu K, Finlayson G, *et al.* (2019) Metabolic adaptations during negative energy balance and their potential impact on appetite and food intake. *Proc Nutr Soc* **78**, 279–289.
- Thivel D, Finlayson G & Blundell JE (2018) Homeostatic and neurocognitive control of energy intake in response to exercise in pediatric obesity: a psychobiological framework. *Obes Rev* **20**, 316–324.
- Thivel D, Rumbold PL, King NA, *et al.* (2016) Acute post-exercise energy and macronutrient intake in lean and obese youth: a systematic review and meta-analysis. *Int J Obes* **40**, 1469–1479.
- Thivel D, Doucet E, Julian V, *et al.* (2017) Nutritional compensation to exercise- *v.* diet-induced acute energy deficit in adolescents with obesity. *Physiol Behav* **176**, 159–164.
- Pélicier L, Julian V, Beaulieu K, *et al.* (2022) Effect of acute dietary- *v.* combined dietary and exercise-induced energy deficits on subsequent energy intake, appetite and food reward in adolescents with obesity. *Physiol Behav* **244**, 113650.
- Fillon A, Pélicier L, Beaulieu K, *et al.* (2023) Dietary- but not exercise-induced acute iso-energetic deficit result in short-term appetitive compensatory responses in adolescents with obesity. *Appetite* **181**, 106401.
- Hägele FA, Büsing F, Nas A, *et al.* (2019) Appetite control is improved by acute increases in energy turnover at different levels of energy balance. *J Clin Endocrinol Metab* **104**, 4481–4491.
- Bosy-Westphal A, Hägele FA & Müller MJ (2021) Impact of energy turnover on the regulation of energy and macronutrient balance. *Obesity* **29**, 1114–1119.
- Burton FL, Malkova D, Caslake MJ, *et al.* (2010) Substrate metabolism, appetite and feeding behaviour under low and high energy turnover conditions in overweight women. *Br J Nutr* **104**, 1249–1259.
- Nas A, Büsing F, Hägele FA, *et al.* (2020) Impact of energy turnover on fat balance in healthy young men during energy balance, energetic restriction and overfeeding. *Br J Nutr* **123**, 30–40.
- Paris HL, Foright RM, Werth KA, *et al.* (2016) Increasing energy flux to decrease the biological drive toward weight regain after weight loss - a proof-of-concept pilot study. *Clin Nutr ESPEN* **11**, e12–e20.
- Hume DJ, Yokum S & Stice E (2016) Low energy intake plus low energy expenditure (low energy flux), not energy surfeit, predicts future body fat gain. *Am J Clin Nutr* **103**, 1389–1396.
- Cole TJ, Bellizzi MC, Flegal KM, *et al.* (2000) Establishing a standard definition for child overweight and obesity worldwide: international survey. *BMJ* **320**, 1240.
- Rowland TW (1996) Does peak VO₂ reflect VO_{2max} in children?: evidence from supramaximal testing. *Med Sci Sports Exerc* **25**, 689–693.
- Pradalé L (2003) Alimentation et santé des lycéens et des collégiens (Food and health for secondary school pupils). Agence Méditerranéenne de l'Environnement (Mediterranean Environment Agency), p. 136. <https://docplayer.fr/1908718-Alimentation-et-sante-des-lyceens-et-des-collegiens.html>
- Thivel D, Genin PM, Mathieu ME, *et al.* (2016) Reproducibility of an in-laboratory test meal to assess ad libitum energy intake in adolescents with obesity. *Appetite* **105**, 129–133.
- Masurier J, Mathieu ME, Fearnbach SN, *et al.* (2018) Effect of exercise duration on subsequent appetite and energy intake in obese adolescent girls. *Int J Sport Nutr Exerc Metab* **28**, 593–601.
- Miguet M, Fillon A, Khammassi M, *et al.* (2018) Appetite, energy intake and food reward responses to an acute high intensity interval exercise in adolescents with obesity. *Physiol Behav* **195**, 90–97.
- Flint A, Raben A, Blundell JE, *et al.* (2000) Reproducibility, power and validity of visual analogue scales in assessment of appetite sensations in single test meal studies. *Int J Obes* **24**, 38–48.
- Drapeau V, King N, Hetherington M, *et al.* (2007) Appetite sensations and satiety quotient: predictors of energy intake and weight loss. *Appetite* **48**, 159–166.
- Finlayson G, King N & Blundell JE (2007) Liking *v.* wanting food: importance for human appetite control and weight regulation. *Neurosci Biobehav Rev* **31**, 987–1002.
- Oustric P, Thivel D, Dalton M, *et al.* (2020) Measuring food preference and reward: application and cross-cultural adaptation of the Leeds Food Preference Questionnaire in human experimental research. *Food Qual Prefer* **80**, 103824.
- Fearnbach SN, Silvert L, Keller KL, *et al.* (2015) Reduced neural response to food cues following exercise is accompanied by decreased energy intake in obese adolescents. *Int J Obes* **40**, 77–83.



31. Thivel D, Isacco L, Montaurier C, *et al.* (2012) The 24-h energy intake of obese adolescents is spontaneously reduced after intensive exercise: a randomized controlled trial in calorimetric chambers. *PLoS One* **7**, e29840.
32. Thivel D, Tremblay MS & Chaput J-P (2013) Modern sedentary behaviors favor energy consumption in children and adolescents. *Curr Obes Rep* **2**, 50–57.
33. Thivel D, Chaput JP, Adamo KB, *et al.* (2014) Is energy intake altered by a 10-week aerobic exercise intervention in obese adolescents? *Physiol Behav* **135**, 130–134.
34. Mayer J, Roy PU & Mitra KP (1956) Relation between caloric intake, body weight, and physical work: studies in an industrial male population in West Bengal. *Am J Clin Nutr* **4**, 169–75.
35. Melby CL, Paris HL, Sayer RD, *et al.* (2019) Increasing energy flux to maintain diet-induced weight loss. *Nutrients* **11**, 2533
36. Janssen I & LeBlanc AG (2010) Systematic review of the health benefits of physical activity and fitness in school-aged children and youth. *Int J Behav Nutr Phys Act* **7**, 1–16.
37. Swift DL, McGee JE, Earnest CP, *et al.* (2018) The effects of exercise and physical activity on weight loss and maintenance. *Prog Cardiovasc Dis* **61**, 206–213.
38. Foright RM, Presby DM, Sherk VD, *et al.* (2018) Is regular exercise an effective strategy for weight loss maintenance? *Physiol Behav* **188**, 86–93.
39. Hopkins M & Blundell JE (2016) Energy balance, body composition, sedentariness and appetite regulation: pathways to obesity. *Clin Sci* **130**, 1615–1628.
40. King NA, Caudwell PP, Hopkins M, *et al.* (2009) Dual-process action of exercise on appetite control: increase in orexigenic drive but improvement in meal-induced satiety. *Am J Clin Nutr* **90**, 921–927.
41. Elfhag K & Rössner S (2005) Who succeeds in maintaining weight loss? A conceptual review of factors associated with weight loss maintenance and weight regain. *Obes Rev* **6**, 67–85.
42. Sumithran P & Proietto J (2013) The defence of body weight: a physiological basis: for weight regain after weight loss. *Clin Sci* **124**, 231–241.
43. Granados K, Stephens BR, Malin SK, *et al.* (2012) Appetite regulation in response to sitting and energy imbalance. *Appl Physiol Nutr Metab* **37**, 323–333.
44. Beaulieu K, Hopkins M, Blundell J, *et al.* (2018) Homeostatic and non-homeostatic appetite control along the spectrum of physical activity levels: an updated perspective. *Physiol Behav* **192**, 23–29.
45. Moghetti P, Bacchi E, Brangani C, *et al.* (2016) Metabolic effects of exercise. *Front Horm Res* **47**, 44–57.