Delayed meal timing after exercise is associated with reduced appetite and energy intake in adolescents with obesity

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Abstract

Background. While the beneficial effects of exercise on appetite might depend on its timing during the day or relative to a meal, this remains poorly explored in youth.

Objectives. To examine the importance of meal timing (+30*vs.*+90minutes) after performing exercise on energy intake, appetite and food reward in adolescents with obesity.

Methods. Eighteen adolescents with obesity randomly completed 3 conditions: i) lunch (12:00pm) set 30min after a rest session (11:00am); ii) lunch (12:00pm) set 30min after an exercise session (11:00 am)(MEAL-30); iii) lunch (01:00pm) set 90min after an exercise session (11:00am)(MEAL-90). Lunch and dinner *ad libitum* energy intake was assessed, food reward (LFPQ) assessed before and after lunch, and before dinner, appetite sensations were assessed at regular intervals.

Results. Energy intake was lower at MEAL-90 than MEAL-30 and CON at lunch ($p<0.05$ and $p<0.01$, respectively) and lunch+dinner combined($p<0.001$). A decrease in intake (g) of protein, fat and carbohydrate was observed. Post-exercise hunger was lower on MEAL-90 compared with CON. No condition effects were found at lunch for food reward.

Conclusions. Delaying the timing of the meal after exercise might help affect energy balance by decreasing *ad libitum* energy intake without increasing hunger and by improving satiety in adolescents with obesity.

Key words. Exercise Timing, Appetite, Energy Intake, Obesity, Adolescent, Food reward

Clinical Trial reference: NCT03968458

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Introduction

While practitioners and clinicians constantly work on the improvement of their weight loss interventions, trying to identify the best exercise characteristics (modality, intensity, duration, etc.) to prescribe, the need to also consider the timing of exercise has been recently suggested [1]. Recent studies effectively show that the beneficial effects of exercise might also depend on its timing during the day or its delay/position regarding a meal [1]. Some studies for instance showed that performing acute exercise one to three hours after a meal could enhance the glycemic response in patients with type II diabetes [2–5] while others showed a better postprandial lipemia response when exercise was performed immediately before the meal [6–8].

Looking at the alarming progression of overweight and obesity among children and adolescents, it seems necessary to deepen our understanding on the effects of exercise on overall energy balance, in order to optimize our weight loss strategies. It is now clear that physical exercise does not only impact energy expenditure, it also affects energy intake and appetite control in youth and adolescents with obesity [9]. The current literature mainly investigated the effect of exercise duration [10,11], intensity [12–14] or modality [15] on subsequent food intake, appetite sensations or food reward, while the potential role played by the timing of exercise remains poorly explored [16].

In 2017, Mathieu and collaborators assessed the effects of exercising immediately before or after a lunch meal in primary school children on overall energy balance [17]. Although they did not observe any difference on energy intake between conditions (before or after the meal), their results highlight the beneficial effect of performing pre-meal moderate-to-vigorous over low-intensity exercise on subsequent energy intake [17]. More recently, similar results were obtained among adolescents with obesity whose energy intake and food reward remained unchanged whether the adolescents performed 30 min of cycling exercise (65% VO_{2peak}) immediately before or after their lunch meal [18]. Interestingly, others investigated the potential effect of the delay between an acute exercise bout and the following meal on energy intake and appetite. In their work, Albert and colleagues compared the effects of exercising (treadmill running at 70% VO_{2max}) 45 min or 180 min before lunch, in normal weight adolescents [19]. The authors observed an 11% reduction of the adolescents' *ad libitum* energy intake and a 23% decrease in fat intake when the exercise was performed 45 min before lunch, compared to 180 min. Moreover, there were no difference in terms of appetite sensations and no energy compensation at the following snack or dinner. Our research group recently examined the effect of the exercise-meal delay on energy intake, appetite and food reward among adolescents with obesity [20]. According to our results, a 30-min cycling exercise bout (65% VO_{2max}) performed 60 min before lunch favored a 14% reduction of *ad libitum* energy intake while the same exercise performed 180 min before lunch did not affect the adolescents' energy intake. While appetite sensations (hunger, fullness, prospective food consumption and desire to eat) did not differ between conditions, our results also showed a significantly lower pre-meal explicit liking for high-fat relative to low-fat foods when the exercise was set close to the meal, suggesting the implication of the food reward system [20]. Altogether, these results seem to show a beneficial effect of exercising close to a meal on overall energy balance in adolescents.

Although these studies compared exercises of similar characteristics (e.g. duration, modality, intensity), their metabolic demand might have been different due to their divergent delay from breakfast, which might have important implications when it comes to subsequent energy intake. Indeed, it has been shown that the metabolic activity during exercise, particularly the contribution of the energy substrates, is different depending on the delay between a breakfast and this exercise [21]. The substrate oxidation during exercise, especially the rate of carbohydrate oxidation has been associated with subsequent energy intake [22], particularly in adults with obesity [23,24]. Investigating the effect of the timing of exercise on appetite and energy intake needs to consider not only its delay with the following meal but also the time interval between exercise and the previous food intake.

In that context, the aim was to examine the importance of meal timing (+30 or +90 minutes) after performing exercise on energy intake, appetite and food reward in adolescents with obesity.

Materials and methods

Participants

Eighteen adolescents with obesity (according to [25]) aged 12-15 years (Tanner stage 3-4) were enrolled in this study (12 boys (12.6 ± 1.2 years) and 6 girls (13.0 ± 1.6 years)). They were recruited through the local Pediatric Obesity Center (Tza Nou, La Bourboule, France), based on the following main inclusion criteria: i) to be free of any medication known to influence appetite or metabolism; ii) to be free of any contraindication to physical activity; iii) to be classified as physically inactive (taking part in less than 2 hours of physical activity per week as assessed using the International Physical Activity Questionnaire –IPAQ [26]). This study was conducted in accordance with the Helsinki declaration and all the adolescents and their legal representative received information sheets and signed consent forms as requested by the local ethical authorities (Human Ethical Committee authorization reference: 2019-A00530-57; Clinical Trial reference: NCT03968458).

1.1. Design

After a preliminary medical inclusion visit performed by a pediatrician to control for the ability of the adolescents to complete the study, they were asked to perform a maximal aerobic test and their body composition was assessed by dual-energy x-ray absorptiometry (DXA). The adolescents thereafter completed the three following experimental sessions (one week apart) in randomized order: i) lunch (at 12:00pm) set 30 min after a rest session (at 11:00 am) ii) lunch (at 12:00pm) set 30 min after an exercise session (at 11:00am; MEAL-30); iii) lunch (at 1:00pm) set 90 min after an exercise session (at 11:00am; MEAL-90). On the three occasions, participants received a standardized breakfast (08:00am) and were asked to remain at rest (CON) or to cycle for 30 min at 11:00am and eat either 30 min (on MEAL-30; lunch at 12:00pm) or 90 min (on MEAL-90; lunch at 1:00pm) after exercise. Dinner was provided to the adolescents at 6:30pm. They were asked to complete the Leeds Food Preference Questionnaire (LFPQ) [27] before and after the lunch meal and before dinner. Lunch and dinner energy intake were assessed via *ad libitum* buffet-style meals. Appetite sensations were measured at regular intervals throughout the day. Outside the experimental conditions and between the two *ad libitum* test meals, the adolescents stayed in the laboratory, devoid of any food cues, and were requested not to engage in any moderate-to-vigorous physical activity and mainly completed sedentary activities such as reading, homework or board games. Figure 1 details the whole design of the study.

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1.2. Anthropometric characteristics and body composition

Body mass and height were measured wearing light clothing while bare-footed, using a digital scale and a standard wall-mounted stadiometer, respectively. Body mass index (BMI) was calculated as body mass (kg) divided by height squared (m^2) and the sex and age dependent French reference curves were used to obtain the BMI percentile [28]. Fat mass (FM) and fat-free mass (FFM) were assessed by dual-energy X-ray absorptiometry (DXA) following standardized procedures (QDR4500A scanner, Hologic, Waltham, MA, USA). These measurements were obtained during the preliminary visit by a trained technician.

1.3. Peak oxygen uptake test ($\dot{V}O_{2peak}$)

Each adolescent performed a $\dot{V}O_{2peak}$ test on a traditional ergometer [29]. The initial power was set at 30W during 3 minutes, followed by a 15W increment every minute until exhaustion. The adolescents were strongly encouraged by the experimenters throughout the test to perform their maximal effort. Maximal criteria were: heart rate >90% of the theoretical maximum heart rate (210 − 0.65 × age), respiratory exchange ratio (RER = $\dot{V}CO_2/\dot{V}O_2$) > 1.1 and/or $\dot{V}O_2$ plateau. Cardiac electrical activity (Ultima SeriesTM, Saint Paul, MN) and heart rate (Polar V800) were monitored and the test was coupled with a measurement of breath-by-breath gas exchanges (BreezeSuite Software, Saint Paul, MN), that determined $\dot{V}O_2$ and $\dot{V}CO_2$. Volumes and gases were calibrated before each test. $\dot{V}O_{2peak}$ was defined as the average of the last 30 s of exercise before exhaustion.

1.4. Experimental conditions

Rest condition (CON): During this condition, the adolescents were asked to remain quiet and were not allowed to engage in any physical activity. They were asked to stay seated on a comfortable chair (30 min) between 11:00am and 11:30am, not being allowed to talk, read, watch TV or to complete any intellectual tasks. Energy expenditure was assessed during the 30-min rest period using portable indirect calorimetry (K4b², COSMED Inc., Rome, Italy).

Lunch condition 30 min after exercise (MEAL-30): Between 11:00am and 11:30am, the participants performed a 30-min moderate-intensity exercise bout (65% VO_{2peak}) on a cycle ergometer. The intensity was controlled by heart rate records (Polar V800) using the results from the maximal aerobic capacity testing. Exercise-induced energy expenditure was calculated based on the results obtained during the maximal oxygen uptake test.

Lunch condition 90 min after exercise (MEAL-90): The adolescents performed the same exercise bout as MEAL-30 and at the same time, but the *ad libitum* lunch meal was served at 1:00pm (90 min after the end of the exercise).

1.5. Energy intake

At 08:00am, the adolescents consumed a standardized calibrated breakfast (500 kcal) respecting the recommendations for their age (composition: bread (50 g), butter (10 g), marmalade (15 g), yoghurt (125 g) or semi-skimmed milk (20 cl), fruit or fruit juice (20 cl)). Lunch and dinner meals were served *ad libitum* using a buffet-type meal. The content of the buffets was determined using a food preference and habits questionnaire filled in by the adolescents during the inclusion visit, as previously described [30]. Top rated items as well as disliked items and items liked but not usually consumed were excluded to avoid over-, under- and occasional consumption. The lunch menu was beef steak, pasta, mustard, cheese, yoghurt, compote, fruits and bread. The dinner menu was ham/turkey, beans, mashed potato, cheese, yoghurt, compote, fruits and bread. Food items were presented in abundance and the adolescents were told to eat until comfortably full. Adolescents made their choices and composed their trays individually before joining their habitual table (5 adolescents per table). Lunch and dinner were served in a quiet environment free of music, cellphones or television. Food items were weighed by the experimenters before and after each meal. Energy intake and macronutrient composition (proportion of fat, carbohydrate and protein) were calculated using the software Bilnut 4.0. This methodology has been previously validated and published [30]. Lunch and total relative energy intake (REI) were calculated such as: energy intake – exercise-induced energy expenditure.

1.6. Subjective appetite sensations

Appetite sensations were collected at regular intervals throughout the day using visual analogue scales (150-mm scales) [31]. Adolescents had to report their hunger, fullness, desire to eat (DTE) and prospective food consumption (PFC) before and immediately after breakfast, prior and after rest (CON) or exercise (MEAL-30 and MEAL-90), before and immediately after lunch, 30 min and 60 min after lunch, before and immediately after dinner.

1.7. Food liking and wanting

The Leeds Food Preference Questionnaire, described in greater methodological detail by Dalton and Finlayson [32], provided measures of food preference and food reward. The adolescents were presented with a culturally (food items and language) adapted version of the LFPQ following the recent recommendations from Oustric and collaborators [33]. Participants were presented with an array of pictures of individual food items common in the diet. Foods were chosen by the local research team from a validated database to be either predominantly high (>50% energy) or low (<20% energy) in fat but similar in familiarity, protein content, palatability and suitable for the study population. The LFPQ has been deployed in a range of research [32] including a recent exercise/appetite trial in young French males [34] and adolescents [20,35,36].

Explicit liking was measured by participants rating the extent to which they like each food ("How pleasant would it be to taste this food now?"). The food images were presented individually, in a randomized order and participants made their ratings using a 100-mm VAS. Implicit wanting was assessed using a forced choice methodology in which the food images were paired so that every image from each of the four food types was compared to every other type over 96 trials (food pairs). Participants were instructed to respond as quickly and accurately as they could to indicate the food they want to eat the most at that time ("Which food do you most want to eat now?"). Reaction times for all responses were covertly recorded and used to compute mean response times for each food type after adjusting for frequency of selection.

Responses on the LFPQ were used to compute mean scores for high-fat, low-fat, sweet or savoury food types (and different fat-taste combinations). Fat bias scores were calculated as the difference between the high-fat scores and the low-fat scores, with positive values indicating greater liking or wanting for high-fat relative to low-fat foods and negative values indicating greater liking or wanting for low-fat relative to high-fat foods. Sweet bias scores were calculated as the difference between the sweet and savoury scores, with positive values indicating greater liking or wanting for sweet relative to savoury foods and negative values indicating greater liking or wanting for savoury relative to sweet foods.

1.8. Statistical analysis

Statistical analyses were performed using Stata software, Version 13 (StataCorp, College Station, TX, US). The sample size estimation was determined according to (i) CONSORT 2010 statement, extension to randomized pilot and feasibility trials (Eldridge et al. CONSORT 2010 statement: extension to randomized pilot and feasibility trials. Pilot and Feasibility Studies (2016) 2:64) and (ii) Cohen's recommendations [37] who has defined effect-size bounds as : small (ES: 0.2), medium (ES: 0.5) and large (ES: 0.8, "'grossly perceptible and therefore large"). So, with 15 patients by condition, an effect-size around 1 can be highlighted for a two-sided type I error at 1.7% (correction due to multiple comparisons), a statistical power greater than 80% and an intra-class correlation coefficient at 0.5 to take into account between and within participant variability. All tests were two-sided, with a Type I error set at 0.05. Continuous data was expressed as mean ± standard deviation (SD) or median [interquartile range] according to statistical distribution. The assumption of normality was assessed by using the Shapiro-Wilk test. Daily (total) area under the curve (AUC) were calculated using the trapezoidal method. Random-effects models for repeated data were performed to compare three conditions (i) considering the following fixed effects: time, condition and time x condition interaction, and (ii) taking into account between and within participant variability (subject as random-effect). A Sidak's type I error correction was applied to perform multiple comparisons. As proposed by some statisticians [38,39] a particular focus will be also given to the magnitude of differences, in addition to inferential statistical tests expressed using p-values. The normality of residuals from these models was studied using the Shapiro-Wilk test. When appropriate, a logarithmic transformation was proposed to achieve the normality of dependent outcome.

2. Results

Eighteen adolescents with obesity participated in this study. Their mean age was 12.7 ± 1.3 years, body weight was 88.9 ± 23.6 kg (with a BMI of 33.3 ± 6.5 kg/m^2 (z-BMI 2.2 ± 0.4), with a percentage of body fat mass of 37.6 ± 5.0 % and a FFM of 53.1 ± 12.5 kg.

The adolescents had a $\dot{V}O_{2peak}$ of 21.8 ± 4.6 ml/min/kg. Energy expenditure induced by the exercise (total duration 30 min) was significantly higher compared to the 30-min resting energy expenditure (168.8 ± 43.6 kcal and 46.9 ± 14.9 kcal, respectively; p<0.001).

Table 1 details the results related to absolute and relative energy intake. At lunch, absolute *ad libitum* energy intake was significantly lower in MEAL-90 than MEAL-30 and CON (p<0.05 and p<0.01, respectively) and in MEAL-30 than CON (p<0.05). Dinner *ad libitum* energy intake was significantly lower in MEAL-90 compared with MEAL-30 (p<0.01) with no difference between the exercise conditions and CON. Total daily absolute *ad libitum* energy intake was significantly lower in MEAL-90 compared with both CON and MEAL-30 (p<0.001).

REI at lunch was significantly higher in CON compared with MEAL-30 and MEAL-90 (p<0.05 and p<0.001, respectively) and total REI was significantly higher in CON compared with MEAL-90 (p<0.001). Both lunch (p<0.05) and total REI (p<0.001) were significantly lower in MEAL-90 than MEAL-30.

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The lunch and total absolute intake of protein, fat were significantly lower in MEAL-90 compared with both CON ($p<0.01$ and $p<0.05$, respectively) and MEAL-30 ($p<0.01$ and $p<0.05$, respectively) while their intake at dinner was significantly lower in MEAL-90 compared with MEAL-30 ($p<0.05$). The absolute intake of CHO was significantly lower in MEAL-90 compared with CON at lunch ($p<0.05$) and significantly higher in MEAL-30 compared with CON at dinner ($p<0.05$). Total absolute CHO intake was only significantly lower in MEAL-90 compared with CON ($p<0.05$). No significant difference was observed between conditions regarding the relative intake of each macronutrient. Table 2 details these results.

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Figure 2 presents the results related to appetite sensations. Fasting hunger, fullness, PFC and DTE did not differ between conditions. After the standardized breakfast, significant differences between conditions were found: hunger and DTE were higher in MEAL-30 than MEAL-90 (p=0.003 and p=0.02), respectively) and CON (p=0.010 and p=0.016, respectively), while PFC was greater in MEAL-30 than MEAL-90 only (p=0.021). Before exercise, hunger was significantly lower during both exercise conditions than during CON ($p<0.001$ for both). After exercise, this difference remained significant only between CON and MEAL-90 (p=0.004). Immediately before lunch, hunger and PFC were significantly lower in MEAL-30 compared with CON (p=0.036 and p=0.041, respectively). Post-lunch sensations were similar between conditions. Pre-dinner hunger was lower during both exercise conditions compared with CON (p=0.006 for MEAL-30 and p=0.003 for MEAL-90). Pre-dinner fullness was greater in MEAL-30 and MEAL-90 compared with CON (p=0.006 and p=0.003, respectively). Regarding pre-dinner DTE and PFC, only MEAL-90 was significantly lower than CON (p=0.006 and p=0.005, respectively). Concerning the daily AUC (Figure 2), relative to CON, hunger and DTE were significantly lower in MEAL-30 (p=0.019 and p=0.05, respectively) and MEAL-90 (p=0.034 and p=0.031, respectively).

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As detailed in Table 3, there was a significant condition effect for pre-dinner explicit liking fat bias (p=0.004), with explicit liking for high-fat foods being lower in MEAL-90 compared with both CON (p=0.001) and MEAL-30 (p=0.004). While explicit liking taste bias significantly decreased in response to the lunch meal during the CON condition (p<0.001), this significant meal effect disappeared during both exercise conditions, without a meal x condition interaction. Implicit wanting taste bias significantly increased in response to the lunch test meal during MEAL-90 (p=0.04), and no meal effect was observed in CON and MEAL-30.

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Discussion

The timing of exercise relative to a meal has been recently highlighted for its influence on energy intake and appetite control [1,16], with some recent studies suggesting a better effect of acute exercise performed close to a meal on energy intake and appetite in both adolescents who are lean [19] and adolescents with obesity [20]. However these studies did not consider the potential impact of the delay between the exercise and the previous breakfast intake. It has been shown that this delay will impact the metabolic nature of exercise such as the substrates used [21], which might, in turn, differently affect subsequent energy intake [22–24]. In that context, the aim of the present study was to investigate the effect of exercise performed at the same delay from breakfast on energy intake, appetite sensations and food reward at the following lunch set either 30 or 90 min after exercise in adolescents with obesity.

According to our results, both exercise conditions (MEAL-30 and MEAL-90) led to significantly lower absolute energy intake at lunch compare to CON. This is in line with previous studies in similar populations showing reduced subsequent intake in response to acute exercise set at the same time of the morning [12,14,20,40]. Interestingly, absolute energy intake was also significantly lower in MEAL-90 compared with MEAL-30, suggesting a greater anorexigenic effect when exercise does not immediately precede the meal. Additionally, total and dinner absolute energy intake were lower during MEAL-90 only, with total daily energy intake reduced by 12% (250 kcal/day) and 16% (352 kcal/day) compared with CON and MEAL-30, respectively. These results are reinforced by a lower lunch relative energy intake after MEAL-30 compared with CON and lower lunch and total REI during MEAL-90 compared with both MEAL-30 and CON. Importantly, while most of the available evidence supports the anorexigenic effect of intensive exercise [13,35,41,42], our results reinforce more recent work also observing reduced food intake in response to moderate-to-vigorous exercise in adolescents and children with obesity [40,40].

While available evidence indicates the beneficial effect of exercising close to a meal on subsequent energy intake [19,20], our results seem to suggest that more than the exercise-meal delay itself, the interval between the exercise and the following eating episode is of importance.

A balanced buffet meal offering several items selected to avoid any over-, under- or occasional-consumption (as previously validated [30]) was offered to adolescents which provided the opportunity to also assess their macronutrient intake. While none of the relative intake of fat, protein and carbohydrate were found different between conditions, their absolute consumption at lunch was reduced only in MEAL-90 compared with CON, and compared with MEAL-30 for protein and lipid. Interestingly, the absolute intake of carbohydrate at dinner increased in MEAL-30 compared with the two other conditions. The macronutrient responses observed in MEAL-90 seem in line with Albert et al. in lean adolescents [19] and with our previous study in adolescents with obesity [20], showing reduced absolute macronutrient intake after moderate exercise set at the end of the morning. The current study however missed to find similar results in MEAL-30, suggesting here the potential importance of the delay between the exercise and the previous eating episode (breakfast). Indeed, in these previous studies, the appetitive responses to exercise set at different times of the morning, and then at different delays from breakfast, were compared, meaning that despite similar duration, modality and intensity, the exercise was not of similar metabolic and energetic load [21], which might explain our results. Unfortunately, it was not possible in the present study to measure the substrate oxidation during exercise and at rest. Furthermore, it remains difficult to reach a consensus regarding the effect of acute exercise on macronutrient intake in lean adolescents and in adolescents with obesity based on the available evidence [42].

Regarding the adolescents' subjective appetite sensations, our results show a lower daily (AUC) hunger and desire to eat in both exercise conditions compared with CON. Although pre-lunch hunger and PFC were significantly lower in MEAL-30 compared with CON, which could have contributed to the lower observed *ad libitum* energy intake, they remained unchanged in MEAL-90 while the decreased food consumption was even more pronounced. This inconsistency between appetite sensations and energy intake reinforce the previously described uncoupling effect of exercise between these sensations and food consumption [43]. Interestingly however, post-lunch sensations were identical between exercise conditions, suggesting a similar satiating effect of lunch meals despite lower intakes in MEAL-30 and particularly in MEAL-90, limiting any potential subsequent compensatory responses. This is even reinforced by the significantly reduced food intake observed at dinner in MEAL-90. This is of particular importance since energy deficits, especially when induced by reduced energy intake, have been shown to generate a subsequent compensatory rise in food intake, with physical exercise limiting or avoiding such a compensation [34,44].

Some recent studies have highlighted the importance of considering the effect of exercise on food reward to better understand its impact on subsequent energy intake in adolescents with obesity [35]. We also assessed whether the liking and wanting for food could be impacted by the delay between eating episodes and exercise in this population. In 2018, Miguet and colleagues observed reduced relative preference for fat and sweet taste, and implicit wanting for high-fat foods (also using the LFPQ) in response to an *ad libitum* meal set 30 minutes after a 16-minute cycling high intensity interval exercise in a similar population [35]. According to the present results, none of the pre or post lunch components of liking and wanting were different between conditions. These results are contradictive with those from Miguet et al. (2018), especially regarding our MEAL-30 condition that had the same delay between the exercise and the meal. However, the exercise intensities were different (high intensity intermittent exercise vs. moderate intensity continuous exercise), reinforcing once more the importance of the exercise intensity in the subsequent control of energy intake. Interestingly, we can see here a significantly lower explicit liking for high-fat food immediately before dinner in MEAL-90 compared with the two others, which might contribute to the observed reduced dinner *ad libitum* food intake. Our results are however also in contradiction with some recently published from our group, showing different food reward responses depending on exercise-meal timing in adolescents with obesity [20]. A lower pre-meal explicit liking for high-fat relative to low-fat foods was observed when the adolescents performed 30 min of moderate intensity cycling 60 min before lunch compared with the same exercise performed 180 min before lunch [20]. The different LFPQ timing between MEAL-90 and the two other conditions must be considered when interpreting our results. Indeed, food reward was assessed pre- and post- lunch meaning that its delay from exercise was different, which might have affected the results. Although there is a growing interest in the effect of exercise on food reward in this population, evidence remains too limited to draw any conclusion and further studies using standardized designs are needed.

The present results must be interpreted in light of some limitations. First, as for the other published studies examining the timing of exercise relative to a meal [16,17,19,20], the lack of direct evaluation of the adolescents' oxygen consumption and substrate oxidation using indirect calorimeters, as well as the lack of a lean control group to examine the potential weight status effect, are the two main limitations. Although the laboratory-based nature of this work constitutes a strength as it allows a better control of the adolescents' activity and intake, it might also not be representative of their habitual daily free-living setting, such as the school setting for instance, as previously underlined by Mathieu et al. in healthy adolescents [17]. Finally, the lack of tracking of the adolescents' food intake over 24 to 48 hours for practical reasons also limits the interpretation of our results [12].

In line with the present work, another potential important factor, while not addressed in the current study, is the timing of exercise (and food intake) with regards to circadian/diurnal rhythms. Emerging evidence suggests that the timing of exercise [45,46] (and food intake [47,48]) impact body weight regulation. Any effects observed from exercise-meal delays may be a result of an interaction with circadian/diurnal oscillations occurring relative to sleep/wake times. Future studies should propose a more complete and integrative exploration of the chronobiologic regulations of energy intake and overall energy metabolism in such adolescents with obesity. Indeed, not only the timings of exercise and /or energy intake should be considered, but also their interactions with the adolescents' sleep, to better understand and potentially regulate their 24-hour circadian rhythm [49,50]. Some key physiological actors of this circadian clock, such as ghrelin and leptin for instance, who are particularly involved in the control of appetite and respondents to sleep and exercise should be mainly considered [51].

Conclusion

To conclude, the present study reinforces the interest in the timing of exercise relative to a meal to affect overall energy balance in youth with obesity; highlighting the importance of the time interval between both the exercise and the previous eating episode, and the exercise and the following meal. According to these results, delaying the timing of the meal after exercise might help reduce energy balance by decreasing *ad libitum* energy intake without increasing hunger and by improving satiety in adolescents with obesity. Future studies should question the importance of the exercise-meal timing on the longer term. While further acute and chronic studies are needed, these results contribute to the current limited body of evidence in the area and seem important in order to optimize weight loss strategies.

Conflicts of interest statement

None and this research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author contributions

AF and DT conceived experiments. AF, MM and MB carried out experiments, AF and DT analysed data. KB was involved in writing the paper and all authors had final approval of the submitted and published versions.

Acknowledgements

The authors are grateful to all of the adolescents that participated in the program, and to the Nutrition Obesity Ambulatory Hospital (UGECAM) that provided their generous support.

Table legends

Table 1: Absolute and Relative Energy Intake in response the three conditions.

Table 2: Macronutrient Intake in response the three conditions.

Table 3: Pre- and Post-test meal food reward on the three experimental conditions

Figures legends

Figure 1 : Study design

Figure 2 : Daily appetite sensations and AUC for hunger, fullness, prospective food consumption and desire to eat

Table 1: Absolute and Relative Energy Intake in response the three conditions.

		CON	MEAL-30	MEAL-90	p	ES		
		Mean (SD)	**Mean (SD)**	**Mean (SD)**		***CON vs.* MEAL-30**	***CON vs.* MEAL-90**	**MEAL-30 *vs.* MEAL-90**
Energy Intake (kcal)	Lunch	1380 (185)	1347 (313)*	1168 (234)^{**a}	0.0143	-0.12[-0.60, 0.35]	-0.71[-1.19, -0.24]	0.59[0.11, 1.06]
	Dinner	796 (294)	931 (260)	748 (245)^{b}	0.0363	0.48[0.00, 0.96]	-0.20[-0.67, 0.28]	0.68[0.20, 1.15]
	Total	2175 (330)	2277 (476)	1925 (360)^{***c}	0.0001	0.27[-0.21, 0.74]	-0.80[-1.28, -0.33]	1.07[0.59, 1.54]
Relative Energy Intake (kcal)	Lunch	1337 (188)	1172 (313)*	1006 (246)^{***a}	0.0003	-0.56[-1.03, -0.08]	-1.08[-1.56, -0.61]	0.52[0.04, 1.00]
	Total	2119 (332)	2110 (489)	1755 (366)^{***c}	<0.0001	-0.11[-0.58, 0.37]	-1.16[-1.63, -0.68]	1.06[0.59, 1.54]

CON: control condition; MEAL-30: Test meal 30 min after exercise; MEAL-90: Test meal 90 min after exercise; SD: Standard Deviation; ES: Effect Size; *p<0.05 vs. CON ; **p<0.01 vs. CON ; ***p<0.001 vs. CON ; ^{a}p<0.05 MEAL-30 vs. MEAL-90 ; ^{b}p<0.01 MEAL-30 vs. MEAL-90 ; ^{c}p<0.001 MEAL-30 vs. MEAL-90; ES: post hoc effect size

Table 2: Macronutrient Intake in response the three conditions.

		CON	MEAL-30	MEAL-90	p	ES		
		Mean (SD)	Mean (SD)	Mean (SD)		*CON vs.* MEAL-30	*CON vs.* MEAL-90	MEAL-30 *vs.* MEAL-90
Proteins (g)	Lunch	73.8 (11.5)	71.9 (17.2)	60.7 (13.9)**[b]	0.0059	-0.13[-0.61, 0.34]	-0.76[-1.24, -0.29]	0.63[0.15, 1.10]
	Dinner	42.0 (18.4)	46.8 (14.4)	37.2 (13.2)[a]	0.1811	0.25[-0.22, 0.73]	-0.30[-0.78, 0.17]	0.56[0.08, 1.03]
	Total	115.9 (22.6)	118.7 (23.8)	98.8 (19.4)***[c]	0.0007	0.08[-0.40, 0.55]	-0.85[-1.32, -0.37]	0.93[0.45, 1.40]
Proteins (%)	Lunch	21.5 (2.3)	21.4 (3.0)	20.8 (2.3)	0.5108	0.05[-0.42, 0.53]	-0.07[-0.55, 0.40]	0.23[-0.25, 0.70]
	Dinner	20.8 (5.2)	19.9 (3.1)	20.1 (3.6)	0.8811	0.17[-0.31, 0.64]	0.01[-0.46, 0.49]	-0.06[-0.53, 0.42]
	Total	21.3 (2.5)	21.0 (2.0)	20.6 (2.3)	0.6248	0.10[-0.38, 0.58]	-0.05[-0.53, 0.42]	0.14[-0.33, 0.62]
Lipids (g)	Lunch	45.4 (9.6)	45.0 (14.2)	38.1 (12.5)*[a]	0.0146	-0.06[-0.53, 0.42]	-0.54[-1.01, -0.06]	0.48[0.06, 1.01]
	Dinner	28.8 (19.0)	33.8 (15.1)	26.1 (14.3)[a]	0.0642	0.33[-0.15, 0.80]	-0.18[-0.66, 0.30]	0.51[0.03, 0.98]
	Total	74.3 (18.0)	78.8 (19.9)	65.8 (19.1)*[b]	0.0123	0.25[-0.23, 0.72]	-0.54[-1.01, -0.06]	0.79[0.31, 1.26]
Lipids (%)	Lunch	29.8 (5.8)	30.3 (8.0)	29.2 (7.3)	0.1910	0.05[-0.42, 0.53]	-0.07[-0.55, 0.40]	0.13[-0.35, 0.60]
	Dinner	30.0 (12.9)	31.3 (10.6)	29.7 (9.8)	0.0277	0.17[-0.31 0.64]	0.01[-0.46, 0.49]	0.15[-0.32, 0.63]
	Total	30.7 (5.8)	31.2 (4.8)	30.5 (5.7)	0.9655	0.10[-0.38, 0.58]	-0.05[-0.53, 0.42]	0.15[-0.32, 0.63]
CHO (g)	Lunch	166.7 (39.4)	160.8 (52.8)	144.2 (34.6)*	0.1649	-0.14[-0.62, 0.33]	-0.52[-0.99, -0.04]	0.37[-0.10, 0.85]
	Dinner	92.8 (31.5)	109.9 (31.5)*	91.9 (29.4)[a]	0.0269	0.52[0.04, 0.99]	-0.036[-0.54, 0.41]	0.58[0.11, 1.06]
	Total	259.5 (56.1)	270.7 (70.0)	233.9 (49.7)[a]	0.0751	0.17[-0.31, 0.64]	-0.45[-0.92, 0.03]	0.61[0.14, 1.09]
CHO (%)	Lunch	48.0 (7.6)	47.5 (10.5)	49.5 (9.1)	0.2149	0.06[-0.53, 0.42]	0.15[-0.33, 0.62]	-0.20[-0.68, 0.27]
	Dinner	49.7 (15.6)	48.9 (12.4)	50.7 (10.7)	0.0840	-0.01[-0.48, 0.47]	0.13[-0.34, 0.61]	-0.14[-0.61, 0.34]
	Total	47.8 (7.4)	47.4 (6.1)	48.7 (7.3)	0.9547	-0.05[-0.53, 0.42]	0.14[-0.34, 0.61]	-0.19[-0.67, 0.28]

CON: control condition; MEAL-30: Test meal 30 minutes after exercise; MEAL-90: Test meal 90 minutes after exercise; SD: Standard Deviation; *p<0.05 vs. CON ; **p<0.01 vs. CON ; ***p<0.001 vs. CON ; [a]p<0.05 MEAL-30 vs. MEAL-90 ; [b]p<0.01 MEAL-30 vs. MEAL-90 ; [c]p<0.001 MEAL-30 vs. MEAL-90; ES: Effect Size; CHO: Carbohydrates; ES: post hoc effect size.

Table 3: Pre- and Post-test meal food reward on the three experimental conditions

	CON	MEAL-30	MEAL-90	p	Interaction time x condition		
	Mean (SD)	**Mean (SD)**	**Mean (SD)**		***CON vs.* MEAL-30**	***CON vs.* MEAL-90**	**MEAL-30 *vs.* MEAL-90**
Implicit Wanting							
Fat Bias							
Before lunch	22.32 (31.15)	19.96 (33.15)	22.80 (31.68)	0.78	0.99	0.58	0.56
After lunch	20.21 (45.58)	17.63 (48.49)	12.61 (29.50)	0.46			
***p before vs. after* lunch**	*0.88*	*0.80*	*0.90*		0.00[-0.48-0.48]	-0.13[-0.61-0.34]	-0.14[-0.62-0.33]
Before dinner	4.37 (64.45)	20.74 (19.89)	14.99 (26.63)	0.49			
Taste Bias							
Before lunch	31.60 (33.67)	34.17 (41.81)	24.90 (32.49)	0.76	0.93	0.14	0.26
After lunch	25.60 (54.02)	27.00 (67.00)	43.59 (30.79)	0.59			
***p before vs. after* lunch**	*0.69*	*0.85*	*0.04*		0.02[-0.45-0.50]	0.36[-0.11-0.84]	0.27[-0.20-0.75]
Before dinner	38.24 (37.81)	40.40 (40.11)	42.30 (28.12)	0.98			
Explicit Liking							
Fat Bias							
Before lunch	10.02 (19.71)	12.52 (16.35)	10.53 (19.64)	0.34	0.57	0.77	0.86
After lunch	5.29 (9.39)	5.14 (10.66)	4.08 (9.25)	0.94			
***p before vs. after* lunch**	*0.27*	*0.03*	*0.11*		-0.14[-0.61-0.34]	-0.07[-0.55-0.40]	0.04[-0.43-0.52]
Before dinner	11.35 (19.83)	9.04 (16.34)	2.44 (13.00)^{***b}	<0.001			
Taste Bias							
Before lunch	26.18 (20.37)	21.95 (23.03)	20.31 (22.89)	0.82	0.10	0.25	0.74
After lunch	12.78 (19.10)	18.08 (25.78)	14.47 (27.62)	0.73			
***p before vs. after* lunch**	*<0.001*	*0.38*	*0.19*		0.40[-0.07-0.88]	0.28[-0.19-0.76]	-0.08[-0.56-0.40]
Before dinner	24.00 (24.58)	21.40 (26.08)	20.76 (28.74)	0.99			

CON: control condition; MEAL-30: Test meal 30 min after exercise; MEAL-90: Test meal 90 min after exercise; SD: Standard Deviation; ***$p<0.001$ vs. CON; $^{b}p<0.01$ MEAL-30 vs. MEAL-90 ; P values and Effect Size are presented for interactions.

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