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

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1 **Delayed meal timing after exercise is associated with reduced appetite and** 2 **energy intake in adolescents with obesity**

3

4 **Abstract**

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

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

9 **Methods.** Eighteen adolescents with obesity randomly completed 3 conditions: i) lunch (12:00pm) set
10 30min after a rest session (11:00am); ii) lunch (12:00pm) set 30min after an exercise session (11:00
11 am)(MEAL-30); iii) lunch (01:00pm) set 90min after an exercise session (11:00am)(MEAL-90). Lunch
12 and dinner *ad libitum* energy intake was assessed, food reward (LFPQ) assessed before and after lunch,
13 and before dinner, appetite sensations were assessed at regular intervals.

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

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

21

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

23 **Clinical Trial reference:** NCT03968458

25 **Introduction**

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

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

41 In 2017, Mathieu and collaborators assessed the effects of exercising immediately before or after a
42 lunch meal in primary school children on overall energy balance ¹⁷. Although they did not observe any
43 difference on energy intake between conditions (before or after the meal), their results highlight the
44 beneficial effect of performing pre-meal moderate-to-vigorous over low-intensity exercise on
45 subsequent energy intake ¹⁷. More recently, similar results were obtained among adolescents with
46 obesity whose energy intake and food reward remained unchanged whether the adolescents
47 performed 30 min of cycling exercise (65% VO_{2peak}) immediately before or after their lunch meal ¹⁸.
48 Interestingly, others investigated the potential effect of the delay between an acute exercise bout and
49 the following meal on energy intake and appetite. In their work, Albert and colleagues compared the
50 effects of exercising (treadmill running at 70% VO_{2max}) 45 min or 180 min before lunch, in normal

51 weight adolescents ¹⁹. The authors observed an 11% reduction of the adolescents' *ad libitum* energy
52 intake and a 23% decrease in fat intake when the exercise was performed 45 min before lunch,
53 compared to 180 min. Moreover, there were no difference in terms of appetite sensations and no
54 energy compensation at the following snack or dinner. Our research group recently examined the
55 effect of the exercise-meal delay on energy intake, appetite and food reward among adolescents with
56 obesity ²⁰. According to our results, a 30-min cycling exercise bout (65% VO_{2max}) performed 60 min
57 before lunch favored a 14% reduction of *ad libitum* energy intake while the same exercise performed
58 180 min before lunch did not affect the adolescents' energy intake. While appetite sensations (hunger,
59 fullness, prospective food consumption and desire to eat) did not differ between conditions, our
60 results also showed a significantly lower pre-meal explicit liking for high-fat relative to low-fat foods
61 when the exercise was set close to the meal, suggesting the implication of the food reward system ²⁰.
62 Altogether, these results seem to show a beneficial effect of exercising close to a meal on overall
63 energy balance in adolescents.

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

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

75

76 **Materials and methods**

77 **Participants**

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

88 **1.1. Design**

89 After a preliminary medical inclusion visit performed by a pediatrician to control for the ability of the
90 adolescents to complete the study, they were asked to perform a maximal aerobic test and their body
91 composition was assessed by dual-energy x-ray absorptiometry (DXA). The adolescents thereafter
92 completed the three following experimental sessions (one week apart) in randomized order: i) lunch
93 (at 12:00pm) set 30 min after a rest session (at 11:00 am) ii) lunch (at 12:00pm) set 30 min after an
94 exercise session (at 11:00am; MEAL-30); iii) lunch (at 1:00pm) set 90 min after an exercise session (at
95 11:00am; MEAL-90). On the three occasions, participants received a standardized breakfast (08:00am)
96 and were asked to remain at rest (CON) or to cycle for 30 min at 11:00am and eat either 30 min (on
97 MEAL-30; lunch at 12:00pm) or 90 min (on MEAL-90; lunch at 1:00pm) after exercise. Dinner was
98 provided to the adolescents at 6:30pm. They were asked to complete the Leeds Food Preference
99 Questionnaire (LFPQ) ²⁷ before and after the lunch meal and before dinner. Lunch and dinner energy
100 intake were assessed via *ad libitum* buffet-style meals. Appetite sensations were measured at regular
101 intervals throughout the day. Outside the experimental conditions and between the two *ad libitum*
102 test meals, the adolescents stayed in the laboratory, devoid of any food cues, and were requested not

103 to engage in any moderate-to-vigorous physical activity and mainly completed sedentary activities
104 such as reading, homework or board games. Figure 1 details the whole design of the study.

105Figure 1.....

106 **1.2. Anthropometric characteristics and body composition**

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

114 **1.3. Peak oxygen uptake test ($\dot{V}O_{2peak}$)**

115 Each adolescent performed a $\dot{V}O_{2peak}$ test on a traditional ergometer ²⁹. The initial power was set at
116 30W during 3 minutes, followed by a 15W increment every minute until exhaustion. The adolescents
117 were strongly encouraged by the experimenters throughout the test to perform their maximal effort.
118 Maximal criteria were: heart rate >90% of the theoretical maximum heart rate ($210 - 0.65 \times \text{age}$),
119 respiratory exchange ratio ($RER = \dot{V}CO_2/\dot{V}O_2$) > 1.1 and/or $\dot{V}O_2$ plateau. Cardiac electrical activity
120 (Ultima SeriesTM, Saint Paul, MN) and heart rate (Polar V800) were monitored and the test was
121 coupled with a measurement of breath-by-breath gas exchanges (BreezeSuite Software, Saint Paul,
122 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
123 defined as the average of the last 30 s of exercise before exhaustion.

124 **1.4. Experimental conditions**

125 *Rest condition (CON)*: During this condition, the adolescents were asked to remain quiet and were not
126 allowed to engage in any physical activity. They were asked to stay seated on a comfortable chair (30

127 min) between 11:00am and 11:30am, not being allowed to talk, read, watch TV or to complete any
128 intellectual tasks. Energy expenditure was assessed during the 30-min rest period using portable
129 indirect calorimetry (K4b², COSMED Inc., Rome, Italy).

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

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

138 **1.5. Energy intake**

139 At 08:00am, the adolescents consumed a standardized calibrated breakfast (500 kcal) respecting the
140 recommendations for their age (composition: bread (50 g), butter (10 g), marmalade (15 g), yoghurt
141 (125 g) or semi-skimmed milk (20 cl), fruit or fruit juice (20 cl)). Lunch and dinner meals were served
142 *ad libitum* using a buffet-type meal. The content of the buffets was determined using a food
143 preference and habits questionnaire filled in by the adolescents during the inclusion visit, as previously
144 described ³⁰. Top rated items as well as disliked items and items liked but not usually consumed were
145 excluded to avoid over-, under- and occasional consumption. The lunch menu was beef steak, pasta,
146 mustard, cheese, yoghurt, compote, fruits and bread. The dinner menu was ham/turkey, beans,
147 mashed potato, cheese, yoghurt, compote, fruits and bread. Food items were presented in abundance
148 and the adolescents were told to eat until comfortably full. Adolescents made their choices and
149 composed their trays individually before joining their habitual table (5 adolescents per table). Lunch
150 and dinner were served in a quiet environment free of music, cellphones or television. Food items
151 were weighed by the experimenters before and after each meal. Energy intake and macronutrient

152 composition (proportion of fat, carbohydrate and protein) were calculated using the software Bilnut
153 4.0. This methodology has been previously validated and published³⁰. Lunch and total relative energy
154 intake (REI) were calculated such as: energy intake – exercise-induced energy expenditure.

155 **1.6. Subjective appetite sensations**

156 Appetite sensations were collected at regular intervals throughout the day using visual analogue scales
157 (150-mm scales)³¹. Adolescents had to report their hunger, fullness, desire to eat (DTE) and
158 prospective food consumption (PFC) before and immediately after breakfast, prior and after rest
159 (CON) or exercise (MEAL-30 and MEAL-90), before and immediately after lunch, 30 min and 60 min
160 after lunch, before and immediately after dinner.

161 **1.7. Food liking and wanting**

162 The Leeds Food Preference Questionnaire, described in greater methodological detail by Dalton and
163 Finlayson³², provided measures of food preference and food reward. The adolescents were presented
164 with a culturally (food items and language) adapted version of the LFPQ following the recent
165 recommendations from Oustric and collaborators³³. Participants were presented with an array of
166 pictures of individual food items common in the diet. Foods were chosen by the local research team
167 from a validated database to be either predominantly high (>50% energy) or low (<20% energy) in fat
168 but similar in familiarity, protein content, palatability and suitable for the study population. The LFPQ
169 has been deployed in a range of research³² including a recent exercise/appetite trial in young French
170 males³⁴ and adolescents^{20,35,36}.

171 Explicit liking was measured by participants rating the extent to which they like each food (“How
172 pleasant would it be to taste this food now?”). The food images were presented individually, in a
173 randomized order and participants made their ratings using a 100-mm VAS. Implicit wanting was
174 assessed using a forced choice methodology in which the food images were paired so that every image
175 from each of the four food types was compared to every other type over 96 trials (food pairs).
176 Participants were instructed to respond as quickly and accurately as they could to indicate the food

177 they want to eat the most at that time (“Which food do you most want to eat now?”). Reaction times
178 for all responses were covertly recorded and used to compute mean response times for each food
179 type after adjusting for frequency of selection.

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

188 **1.8. Statistical analysis**

189 Statistical analyses were performed using Stata software, Version 13 (StataCorp, College Station, TX,
190 US). The sample size estimation was determined according to (i) CONSORT 2010 statement, extension
191 to randomized pilot and feasibility trials (Eldridge et al. CONSORT 2010 statement: extension to
192 randomized pilot and feasibility trials. *Pilot and Feasibility Studies* (2016) 2:64) and (ii) Cohen’s
193 recommendations³⁷ who has defined effect-size bounds as : small (ES: 0.2), medium (ES: 0.5) and large
194 (ES: 0.8, “grossly perceptible and therefore large”). So, with 15 patients by condition, an effect-size
195 around 1 can be highlighted for a two-sided type I error at 1.7% (correction due to multiple
196 comparisons), a statistical power greater than 80% and an intra-class correlation coefficient at 0.5 to
197 take into account between and within participant variability. All tests were two-sided, with a Type I
198 error set at 0.05. Continuous data was expressed as mean \pm standard deviation (SD) or median
199 [interquartile range] according to statistical distribution. The assumption of normality was assessed
200 by using the Shapiro-Wilk test. Daily (total) area under the curve (AUC) were calculated using the
201 trapezoidal method. Random-effects models for repeated data were performed to compare three

202 conditions (i) considering the following fixed effects: time, condition and time x condition interaction,
203 and (ii) taking into account between and within participant variability (subject as random-effect). A
204 Sidak's type I error correction was applied to perform multiple comparisons. As proposed by some
205 statisticians^{38,39} a particular focus will be also given to the magnitude of differences, in addition to
206 inferential statistical tests expressed using p-values. The normality of residuals from these models was
207 studied using the Shapiro-Wilk test. When appropriate, a logarithmic transformation was proposed to
208 achieve the normality of dependent outcome.

209

210 **2. Results**

211 Eighteen adolescents with obesity participated in this study. Their mean age was 12.7 ± 1.3 years,
212 body weight was 88.9 ± 23.6 kg (with a BMI of 33.3 ± 6.5 kg/m² (z-BMI 2.2 ± 0.4), with a percentage of
213 body fat mass of 37.6 ± 5.0 % and a FFM of 53.1 ± 12.5 kg.

214 The adolescents had a $\dot{V}O_{2peak}$ of 21.8 ± 4.6 ml/min/kg. Energy expenditure induced by the exercise
215 (total duration 30 min) was significantly higher compared to the 30-min resting energy expenditure
216 (168.8 ± 43.6 kcal and 46.9 ± 14.9 kcal, respectively; $p < 0.001$).

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

223 REI at lunch was significantly higher in CON compared with MEAL-30 and MEAL-90 ($p < 0.05$ and
224 $p < 0.001$, respectively) and total REI was significantly higher in CON compared with MEAL-90 ($p < 0.001$).
225 Both lunch ($p < 0.05$) and total REI ($p < 0.001$) were significantly lower in MEAL-90 than MEAL-30.

226Table 1.....

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

235Table 2.....

236 Figure 2 presents the results related to appetite sensations. Fasting hunger, fullness, PFC and DTE did
237 not differ between conditions. After the standardized breakfast, significant differences between
238 conditions were found: hunger and DTE were higher in MEAL-30 than MEAL-90 ($p=0.003$ and $p=0.02$),
239 respectively) and CON ($p=0.010$ and $p=0.016$, respectively), while PFC was greater in MEAL-30 than
240 MEAL-90 only ($p=0.021$). Before exercise, hunger was significantly lower during both exercise
241 conditions than during CON ($p<0.001$ for both). After exercise, this difference remained significant
242 only between CON and MEAL-90 ($p=0.004$). Immediately before lunch, hunger and PFC were
243 significantly lower in MEAL-30 compared with CON ($p=0.036$ and $p=0.041$, respectively). Post-lunch
244 sensations were similar between conditions. Pre-dinner hunger was lower during both exercise
245 conditions compared with CON ($p=0.006$ for MEAL-30 and $p=0.003$ for MEAL-90). Pre-dinner fullness
246 was greater in MEAL-30 and MEAL-90 compared with CON ($p=0.006$ and $p=0.003$, respectively).
247 Regarding pre-dinner DTE and PFC, only MEAL-90 was significantly lower than CON ($p=0.006$ and
248 $p=0.005$, respectively). Concerning the daily AUC (Figure 2), relative to CON, hunger and DTE were
249 significantly lower in MEAL-30 ($p=0.019$ and $p=0.05$, respectively) and MEAL-90 ($p=0.034$ and $p=0.031$,
250 respectively).

251Figure 2.....

252

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

260Table 3.....

261 Discussion

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

272 According to our results, both exercise conditions (MEAL-30 and MEAL-90) led to significantly lower
273 absolute energy intake at lunch compare to CON. This is in line with previous studies in similar
274 populations showing reduced subsequent intake in response to acute exercise set at the same time of
275 the morning ^{12,14,20,40}. Interestingly, absolute energy intake was also significantly lower in MEAL-90
276 compared with MEAL-30, suggesting a greater anorexigenic effect when exercise does not

277 immediately precede the meal. Additionally, total and dinner absolute energy intake were lower
278 during MEAL-90 only, with total daily energy intake reduced by 12% (250 kcal/day) and 16% (352
279 kcal/day) compared with CON and MEAL-30, respectively. These results are reinforced by a lower
280 lunch relative energy intake after MEAL-30 compared with CON and lower lunch and total REI during
281 MEAL-90 compared with both MEAL-30 and CON. Importantly, while most of the available evidence
282 supports the anorexigenic effect of intensive exercise ^{13,35,41,42}, our results reinforce more recent work
283 also observing reduced food intake in response to moderate-to-vigorous exercise in adolescents and
284 children with obesity ^{40,40}.

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

288 A balanced buffet meal offering several items selected to avoid any over-, under- or occasional-
289 consumption (as previously validated ³⁰) was offered to adolescents which provided the opportunity
290 to also assess their macronutrient intake. While none of the relative intake of fat, protein and
291 carbohydrate were found different between conditions, their absolute consumption at lunch was
292 reduced only in MEAL-90 compared with CON, and compared with MEAL-30 for protein and lipid.
293 Interestingly, the absolute intake of carbohydrate at dinner increased in MEAL-30 compared with the
294 two other conditions. The macronutrient responses observed in MEAL-90 seem in line with Albert et
295 al. in lean adolescents ¹⁹ and with our previous study in adolescents with obesity ²⁰, showing reduced
296 absolute macronutrient intake after moderate exercise set at the end of the morning. The current
297 study however missed to find similar results in MEAL-30, suggesting here the potential importance of
298 the delay between the exercise and the previous eating episode (breakfast). Indeed, in these previous
299 studies, the appetitive responses to exercise set at different times of the morning, and then at
300 different delays from breakfast, were compared, meaning that despite similar duration, modality and
301 intensity, the exercise was not of similar metabolic and energetic load ²¹, which might explain our

302 results. Unfortunately, it was not possible in the present study to measure the substrate oxidation
303 during exercise and at rest. Furthermore, it remains difficult to reach a consensus regarding the effect
304 of acute exercise on macronutrient intake in lean adolescents and in adolescents with obesity based
305 on the available evidence ⁴².

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

319 Some recent studies have highlighted the importance of considering the effect of exercise on food
320 reward to better understand its impact on subsequent energy intake in adolescents with obesity ³⁵.
321 We also assessed whether the liking and wanting for food could be impacted by the delay between
322 eating episodes and exercise in this population. In 2018, Miguet and colleagues observed reduced
323 relative preference for fat and sweet taste, and implicit wanting for high-fat foods (also using the
324 LFPQ) in response to an *ad libitum* meal set 30 minutes after a 16-minute cycling high intensity interval
325 exercise in a similar population ³⁵. According to the present results, none of the pre or post lunch
326 components of liking and wanting were different between conditions. These results are contradictory

327 with those from Miguet et al. (2018), especially regarding our MEAL-30 condition that had the same
328 delay between the exercise and the meal. However, the exercise intensities were different (high
329 intensity intermittent exercise vs. moderate intensity continuous exercise), reinforcing once more the
330 importance of the exercise intensity in the subsequent control of energy intake. Interestingly, we can
331 see here a significantly lower explicit liking for high-fat food immediately before dinner in MEAL-90
332 compared with the two others, which might contribute to the observed reduced dinner *ad libitum*
333 food intake. Our results are however also in contradiction with some recently published from our
334 group, showing different food reward responses depending on exercise-meal timing in adolescents
335 with obesity ²⁰. A lower pre-meal explicit liking for high-fat relative to low-fat foods was observed
336 when the adolescents performed 30 min of moderate intensity cycling 60 min before lunch compared
337 with the same exercise performed 180 min before lunch ²⁰. The different LFPQ timing between MEAL-
338 90 and the two other conditions must be considered when interpreting our results. Indeed, food
339 reward was assessed pre- and post- lunch meaning that its delay from exercise was different, which
340 might have affected the results. Although there is a growing interest in the effect of exercise on food
341 reward in this population, evidence remains too limited to draw any conclusion and further studies
342 using standardized designs are needed.

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

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

363

364 **Conclusion**

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

374

375 **Conflicts of interest statement**

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

378

379

380 **Author contributions**

381 AF and DT conceived experiments. AF, MM and MB carried out experiments, AF and DT analysed data.

382 KB was involved in writing the paper and all authors had final approval of the submitted and published

383 versions.

384

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388

389 **Table legends**

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

391 Table 2: Macronutrient Intake in response the three conditions.

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

393

394

395 **Figures legends**

396 Figure 1 : Study design

397 Figure 2 : Daily appetite sensations and AUC for hunger, fullness, prospective food consumption and

398 desire to eat

399

400 **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]

401 CON: control condition; MEAL-30: Test meal 30 min after exercise; MEAL-90: Test meal 90 min after exercise; SD: Standard
 402 Deviation; ES: Effect Size; *p<0.05 vs. CON ; **p<0.01 vs. CON ; ***p<0.001 vs. CON ; ^ap<0.05 MEAL-30 vs. MEAL-90 ;
 403 ^bp<0.01 MEAL-30 vs. MEAL-90 ; ^cp<0.001 MEAL-30 vs. MEAL-90; ES: post hoc effect size

404

405 **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)** ^{3c}	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]

406 CON: control condition; MEAL-30: Test meal 30 minutes after exercise; MEAL-90: Test meal 90 minutes after exercise; SD:
 407 Standard Deviation; *p<0.05 vs. CON ; **p<0.01 vs. CON ; ***p<0.001 vs. CON ; ^ap<0.05 MEAL-30 vs. MEAL-90 ; ^bp<0.01
 408 MEAL-30 vs. MEAL-90 ; ^cp<0.001 MEAL-30 vs. MEAL-90; ES: Effect Size; CHO: Carbohydrates; ES: post hoc effect size.

409

410 **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							
<i>Fat Bias</i>							
Before lunch	22.32 (31.15)	19.96 (33.15)	22.80 (31.68)	0.78			
After lunch	20.21 (45.58)	17.63 (48.49)	12.61 (29.50)	0.46	0.99	0.58	0.56
<i>p before vs. after lunch</i>	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			
<i>Taste Bias</i>							
Before lunch	31.60 (33.67)	34.17 (41.81)	24.90 (32.49)	0.76			
After lunch	25.60 (54.02)	27.00 (67.00)	43.59 (30.79)	0.59	0.93	0.14	0.26
<i>p before vs. after lunch</i>	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							
<i>Fat Bias</i>							
Before lunch	10.02 (19.71)	12.52 (16.35)	10.53 (19.64)	0.34			
After lunch	5.29 (9.39)	5.14 (10.66)	4.08 (9.25)	0.94	0.57	0.77	0.86
<i>p before vs. after lunch</i>	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			
<i>Taste Bias</i>							
Before lunch	26.18 (20.37)	21.95 (23.03)	20.31 (22.89)	0.82			
After lunch	12.78 (19.10)	18.08 (25.78)	14.47 (27.62)	0.73	0.10	0.25	0.74
<i>p before vs. after lunch</i>	<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			

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

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