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Comparison of energy-matched high-intensity interval and moderate-intensity continuous exercise sessions on latency to eat, energy intake, and appetite

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Abstract

High-intensity interval exercises (HII_{ex}) have gained popularity but their effects on eating behavior are poorly known. The aim of this study was to evaluate whether the effects of HII_{ex} on the three main components of eating behavior (appetite, intake, and latency to eat) differ from those of moderate-intensity continuous exercises (MIC_{ex}) matched for energy expenditure. Fifteen young normal-weight males completed three sessions in a counterbalanced order: HII_{ex} (30-s bouts at 90% of VO_{2max} interceded with 60-s bouts at 35% of VO_{2max} for 20 min), MIC_{ex} (42% of VO_{2max} for 40 min), and a resting session (REST). Trials were scheduled 80 and 100 min after a standard breakfast for MIC_{ex} and HII_{ex}, respectively. At 120 min, participants were isolated until they asked for lunch. Appetite was rated on four visual analog scales (hunger, desire to eat, fullness, and prospective consumption) every 15 min until meal request. Results showed that the mean latency of requesting lunch was significantly longer after HII_{ex} than after REST ($+17.3 \pm 4.3$ min, $P = 0.004$), but not after MIC_{ex} ($P = 0.686$). Energy intake was not different between conditions, leading to a negative energy balance in the two exercise sessions. Thus, the effects of HII_{ex} on eating behavior are likely primarily mediated through the latency of meal initiation. However, inter-individual variability was large and further studies are needed to identify the predictive factors of this response.

Keywords: exercise; high-intensity interval; appetite; energy intake; latency to eat; hunger, macronutrients

Résumé

Les exercices intermittents de haute-intensité (HII_{ex}) ont gagné en popularité mais leurs effets sur le comportement alimentaire sont mal connus. Le but de cette étude était de savoir si les effets des HII_{ex} sur les trois principales composantes du comportement alimentaire (appétit, prise énergétique et délai de demande de repas) différaient de ceux des exercices continus d'intensité modérée (MIC_{ex}) pour la même dépense énergétique. Quinze jeunes hommes normopondéraux réalisèrent trois sessions dans un ordre aléatoire : HII_{ex} (30 sec à 90% VO_{2max} alternant avec 60 sec à 35 % de VO_{2max} pendant 20 min), MIC_{ex} (42% de VO_{2max} maintenue pendant 40 min) et repos (REST). Les exercices étaient programmés 80 et 100 min après consommation d'un petit déjeuner standard pour respectivement MIC_{ex} et HII_{ex}. A 120 min, les participants étaient isolés jusqu'à ce qu'ils demandent leur déjeuner. L'appétit était évalué par quatre échelles analogiques visuelles (faim, désir de manger, plénitude gastrique et consommation prospective) toutes les 15 min jusqu'à la demande du repas. Les résultats montraient que le délai de demande de repas était significativement augmenté après HII_{ex} comparé à REST (+17.3 ± 4.3 min, $P = 0.004$) mais pas après MIC_{ex} ($P = 0.686$). La prise énergétique au repas n'était pas différente entre les sessions, aboutissant à une balance énergétique négative dans les deux sessions d'exercices. Ainsi, les effets de HII_{ex} sur le comportement alimentaire semblent principalement porter sur le délai de demande de repas. Cependant, la variabilité individuelle était importante et des études sont nécessaires pour identifier des facteurs prédictifs de cette réponse.

Mots-clés: Exercice; exercice intermittent de haute intensité; appétit; prise énergétique; délai de demande de repas ; faim ; macronutriments.

Introduction

Physical activity is increasingly practiced to lose weight, without dieting, through a negative energy balance induced by the exercise session. To succeed, this strategy requires, at least in the short-term, that the expended energy is not fully compensated at the following meal. Most published studies have shown that unlike energy deficits induced by dietary restriction, that are more accurately compensated (Thivel et al. 2018), compensation after exercise is, at best, incomplete and often poor (Elder and Roberts 2007; Deighton and Stensel 2014). However, when authors show individual results, compensation is clearly characterized by a large inter-individual variability (Church et al. 2009; Finlayson et al. 2009; Unick et al. 2010; Charlot et al. 2013; Hopkins et al. 2013; King et al. 2013). Thus, any conclusions concerning the expected compensation for a specific individual appear to be unreliable.

Most studies on energy compensation following an exercise session have been conducted using moderate-intensity continuous exercises (MIC_{ex}). In recent years, high-intensity interval exercises (HII_{ex}), alternating bouts of high and low-intensity exercises, or even passive recovery, have gained popularity. To this day, studies assessing the effects of HII_{ex} on energy compensation have reported results similar to those with MIC_{ex} (Deighton et al. 2013a; Deighton et al. 2013b; Martins et al. 2015). Since the energy expended during a HII_{ex} session is often lower than during a MIC_{ex} session, the energy balance is therefore less negative (Deighton et al. 2013a). When energy expenditure (EE) and duration of the sessions were matched between exercise modalities, HII_{ex} , but not MIC_{ex} , reduced energy intake (EI) in overweight men (Sim et al. 2014), but not in young lean men or women (Deighton et al. 2013b; Shamlan et al. 2017), and resulted in a greater negative energy balance.

To study the mechanisms of post-exercise energy compensation, it is necessary to explore two other components of eating behavior: appetite and latency to eat (Chapelot 2013). Most studies have assessed appetite using scales to rate sensations, such as hunger, gastric fullness, or satiety. Most reported no change in appetite scores, but some a small and transient (0 to 60 min, depending on the studies) decrease in appetite scores after the exercise relative to the rest session (King et al. 1994; King and Blundell 1995; Broom et al. 2007; Burns et al. 2007; Douglas et al. 2017). Results comparing HII_{ex} and MIC_{ex} sessions showed that the post-exercise reduction in hunger after HII_{ex} was either not observed (Deighton et al. 2013), greater than after MIC_{ex} (Williams et al. 2013), or similar (Howe et al. 2016).

Contrary to appetite, the latency to eat has rarely been assessed. This is an important shortcoming, because the time between two meals spontaneously initiated has been shown to be a major determinant of food intake in animals (Le Magnen and Devos 1970; Larue-Achagiotis and Le Magnen 1980) and the first variable of eating pattern modified in response of an energy challenge (Davies 1977; Strubbe and van Dijk 2002). MIC_{ex} was reported to delay the initiation of a meal when participants were exposed to food (King et al. 1994; King and Blundell 1995; King et al. 2013). However, the effect of HII_{ex} on such latency has never been explored.

The objective of the present study was to assess whether a HII_{ex} session exerts different effects on the various components of eating behavior (intake, appetite and delay to eat) than a MIC_{ex} session matched for EE.

Materials and methods

Participants

Participants were recruited through an announcement on a notice board in the Paris 13 University area (Paris, France). Inclusion criteria were that the volunteers be male, healthy, and between 18 and 25 years old. Smokers, individuals who drank alcohol more than occasionally (more than three drinks per week), had food allergies, or took medication were excluded from the study. Volunteers were also excluded if they reported any personal medical history or any familial history of sudden death during exercise. Any current obesity (BMI > 30), change in body weight > 5 kg over the year prior to the study, or a high dietary restraint score (> 26) on the Three-Factor Eating Questionnaire-R18 (Karlsson et al. 2000) were also exclusion criteria. Furthermore, volunteers had to consume at least three meals every day, including breakfast, lunch and dinner, with at least 10% represented by breakfast. Finally, participants had to like each of the items provided at breakfast or lunch and eat them on a regular basis.

Based upon a previous study that found a 46 min delay of meal request after an exercise session (King et al. 2013), it was calculated that with an alpha value of 5% and a statistical power of 80%, 12 participants were necessary. Eighteen participants were initially recruited. Three were unable to satisfy all the mandatory requirements of the procedure and were therefore excluded. Fifteen were finally included in the analyses.

The characteristics of the 15 included participants are shown in Table 1. Body fat mass was assessed using an eight-electrode bioelectrical impedance analyzer (Tanita BC 418MA, Tanita Co). The measurement of maximal oxygen uptake (VO_{2max}) is described below.

This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures were approved by the French National Ethics Committee n°10. Written informed consent was obtained from all participants and all received financial compensation for their participation.

Preliminary testing

At least three days before the first experimental session, the $\text{VO}_{2\text{max}}$ was determined by incremental workload until volitional exhaustion on a bicycle ergometer (Ergoselect 100P, Ergoline, Bitz, Germany). Gas exchange rates were measured by open-circuit spirometry using Vmax Encore (Viasys Healthcare, Palm Springs, CA, USA). Heart rate (HR) was monitored by a 12-electrode Cardiosoft electrocardiogram (Viasys Healthcare). After a 2-min warm-up at 60 W, intensity was increased by 20 W every minute. The $\text{VO}_{2\text{max}}$ was considered to have been reached when an intensity level was completed with the two following criteria: 1) less than $< 2 \text{ ml kg}^{-1} \text{ min}^{-1} \text{ VO}_2$ increase compared to the previous level and 2) a respiratory exchange ratio (RER) > 1.15 . A new $\text{VO}_{2\text{max}}$ determination was scheduled at least three days later if these two criteria were not fulfilled before the participant reached exhaustion.

Study design and procedure

The study followed a within-subject design with participants each completing three test conditions: Rest (REST), HII_{ex} , and MIC_{ex} . The conditions were tested in a randomized counterbalanced order at one-week intervals. Participants were asked to maintain their normal eating habits and physical activity for the 24 h preceding each session and to eat the same dinner at the same hour the evening preceding each session. No food was allowed after this meal. This recommendation was verified using a personal diary

completed by participants and checked by the investigator on arrival at the laboratory. They were asked to take a car or public transport to come to the laboratory, avoiding any physical activity bias across conditions.

The procedure of the experiment is described in Figure 1. Participants arrived at the laboratory after an overnight fast at 8:15 and were served breakfast at 8:20. They had 10 min to entirely consume it. Thus, 08:30 was designated t_0 . According to the randomization, participants remained at rest, performed a MIC_{ex} from 09:50 to 10:30 or a HII_{ex} from 10:10 to 10:30. The end of the exercise occurred 120 min after the completion of breakfast and was designated t_{120} . According to our previously described procedure (Charlot et al. 2011), the participant was then placed in an isolated room deprived of time cues (no computer, smartphone, or watch) and had to spontaneously request his lunch by pressing the button of a visual alarm when he felt the need to eat. All participants were students accustomed to working at a table with paper and books (lectures to learn). However, three asked to watch a movie. They were allowed to do so, but the movies were checked to ensure that they were not stressful, emotional and that there were no scenes related to food intake. Moreover, each participant had to maintain the same activities (work or watching a movie) for all three sessions. Appetite was evaluated using visual analog scales (VAS) every 30 min from t_0 to t_{120} and every 15 min from t_{120} until meal request. Immediately after, EE was measured for 10 min prior to lunch being served. The time to eat was not limited. To avoid any premature meal request, participants were informed that they would not be authorized to leave the laboratory unit before 2:00 PM, a time that was found to largely exceed the longest expected delay for initiating lunch.

Foods

EI from breakfast was calculated according to individual body weight (27 kJ kg^{-1}) and provided $1,908 \pm 315 \text{ kJ}$ (mean $\pm$ SD). It consisted of white bread ($62.2 \pm 10.2 \text{ g}$), butter ($8.4 \pm 2.6 \text{ g}$), strawberry jelly ($26.6 \pm 11.0 \text{ g}$), milk ($186.9 \pm 36.8 \text{ g}$), chocolate powder ($7.8 \pm 1.7 \text{ g}$), and orange juice ($122.2 \pm 37.4 \text{ g}$). Macronutrient proportions were calculated to mimic a traditional French breakfast (66, 24, and 10% of carbohydrate, fat, and protein, respectively).

Lunch consisted of a main dish served in large amounts to encourage an *ad libitum* intake, as in our previous studies (Chapelot and Payen 2009; Charlot and Chapelot 2013). Although it precluded observing differences in macronutrient intake, it was preferred to the buffet-type meal that often results in over-consumption and may induce selection of different items at each session for the sole purpose of variety. This procedure has been found to provide a reliable measurement of energy compensation after an exercise session (Laan et al. 2011). The main dish consisted of spaghetti Bolognese (pasta, tomato sauce, and minced meat; $1,350 \text{ g}$ served, providing 5.4 kJ g^{-1} with 53, 26, and 21% from carbohydrates, fat, and protein, respectively) prepared at the laboratory kitchen by the same investigator and with a fixed cooking time to avoid any difference in sensory properties. To simulate a real-life lunch and allow some specific macronutrient compensation to occur, three items were added: bread (120 g served, 11.4 kJ g^{-1} with 82, 5, and 13% from carbohydrate, fat, and protein, respectively) with the main dish and stewed apples ($1,000 \text{ g}$ served, 3.7 kJ g^{-1} with 100, 0, and 0% from carbohydrate, fat and protein, respectively) and biscuit (67 g served, 18.3 kJ g^{-1} with 69, 25, and 7% from carbohydrate, fat, and protein, respectively) for dessert, only served after the main dish. These items were not considered to induce a variety factor, such as

in a buffet-type meal. All foods were freshly prepared on the morning of each session day, chilled in a refrigerator, and then reheated in an oven when required. All the food items were served to the participant on an individual tray in the isolating room. Water was also provided *ad libitum*. Intake was determined by accurately weighing the amount of food served and the leftovers on an electronic scale (Mettler PM3000, accuracy: 0.1 g). This was concealed from participants who were told that the study was conducted to compare the effects of two types of exercise modalities on oxidized substrates at the onset of a spontaneously initiated meal.

Exercise characteristics

Exercises were practiced on the same bicycle ergometer than for the VO_{2max} determination. The characteristics of the HII_{ex} were chosen to be easily applied to any population, to shorten the time of practice and to have been shown to be beneficial for various health risk factors. Thus, the chosen HII_{ex} trial consisted of 13 bouts of 30 s completed at 90% VO_{2max} , preceded and interceded by bouts of 60 s at 35% VO_{2max} , *i.e.*, a work:recovery ratio of 1:2, the whole session lasting 20 min. The MIC_{ex} trial was planned to require the same EE as the HII_{ex} and to fulfill the criteria of moderate exercise as stated by Norton *et al.* (2010). It thus consisted of 40 min at a minimum of 40% VO_{2max} . Pre-tests were performed by members of the laboratory, with different fitness levels, to verify that the two types of trials resulted in similar EE and that the HII_{ex} could be completed by individuals with different fitness levels. The targeted EE (~1000 kJ) was based on similar studies (Sim *et al.* 2014; Shamlan *et al.* 2017). We chose to adjust the length and intensity of the MIC_{ex} session such that the EE was similar to that of the HII_{ex} session. During the experiment, our choice of the MIC_{ex} session proved to be a valid

duration $\times$ intensity volume to match the EE between exercise modalities. Participants were instructed to maintain their rpm cadency throughout the session and the variations of resistance so that the power would match the planned percentage of VO_{2max} . We used the VO_{2max} test to identify intensities corresponding to 90, 35 (for HII_{ex}) and 40% (for MIC_{ex}) % of VO_{2max} . After each high-intensity bout of the HII_{ex} session and at the end of the exercise sessions, participants rated perceived exertion scales (Borg 6-to-20 graduated scale). To reduce the role of dehydration and thirst in further intake the participants were required to drink an amount of water that matched the exercise-induced weight loss.

Energy expenditure and substrate oxidation

EE and substrate oxidation were assessed during the 40 min of the trial and at the meal request using the same equipment as that for the VO_{2max} determination. During sedentary periods (*i.e.*, during the 40 min of the REST condition, the 20 min prior to the HII_{ex} and at meal request) the EE was calculated by the energy equivalent of O_2 , derived from the Weir equation (1949), and substrate oxidation was calculated using the Peronnet & Massicotte equations (1991), with the assumption that protein oxidation is negligible. During both exercises, the Jeukendrup & Wallis equations (2005) were used to assess substrate oxidation and EE.

Appetite and liking of the foods

Appetite was separated into four components that evaluate different perceptions: hunger, desire to eat, fullness, and prospective consumption. Appetite and liking were assessed on classic 100 mm VAS preceded by the following questions: "How hungry do

you feel?" (hunger scale); "How strong is your desire to eat something?" (desire to eat scale); "How full do you feel?" (fullness scale), and "What quantity of food would you be able to eat?" (prospective consumption scale). After lunch, liking of the food item was assessed using a VAS preceded by the question: "Did you like this food item?". Global liking of the meal ("did you like the whole meal?") was also asked. These scales were anchored with "not at all" and "extremely" at the left and right ends, respectively. The distance from the extreme left to the participant's vertical dash represented the rating score, expressed in mm. These scales have been shown to have a good level of reliability, reproducibility and have some predictability power (Stubbs et al. 2000). They are to this day extensively used to assess satiety (King et al. 1994; Broom et al. 2007; Charlot and Chapelot 2013; Deighton et al. 2013).

Data analysis

EI was analyzed in absolute (EI) and relative (REI) values. REI corresponds to EI corrected for the energy cost of exercise above the resting level, *i.e.*, EI at REST and EI minus exercise-induced EE for MIC_{ex} and HII_{ex}. Energy compensation (EC) was calculated as the percentage of energy adjustment, *e.g.* $EC = [(EI_{HIIex} - EI_{REST}) / (EE_{HIIex} - EE_{REST})] \times 100$. A score of 100% would reflect complete compensation, whereas lower or higher scores would reflect under- or overcompensation, respectively, and a negative score, an increased energy deficit. The macronutrient composition of food intake was calculated in absolute values and percentages of EI. The latency of meal request was calculated (in min) as the time between the end of the trial (t120) and the spontaneous meal request. Appetite scores were assessed separately before and after the exercise trial. The pre-trial profile consisted of the t0 to t60 (60 min after t0, the last scale rated

before the earlier exercise session) scores. The post-trial profile started at the end of the trial (t120) and ended with the first lunch request across participants and conditions. Finally, a pre-lunch profile was analyzed to evaluate whether lunch was requested after a different appetite sequence and level, depending on the type of trial.

Data were analyzed using SYSTAT Software (version 10.1, SPSS, Chicago, IL). Most variables were analyzed using a one-way repeated-measure ANOVA with condition (REST, MIC_{ex}, and HII_{ex}) as the within-subject factor. For appetite scores, a time × condition two-way ANOVA was conducted for each profile (pre-trial, post-trial, and pre-lunch). The Shapiro-Wilk test was used to verify that the data were normally distributed. When an effect of condition or an interaction between condition and group was significant, *post hoc* comparisons of the means were carried out between conditions using Students paired *t* tests. Holm-Bonferroni correction was used for multiple comparisons. Finally, the Pearson product moment correlation coefficient was used to explore relationships between the responses of variables to MIC_{ex} and HII_{ex}.

The effect sizes (ES) of the differences (*d*) were calculated based on the pooled SD, *r*-adjustment, and Hedges' bias correction. Cohen's categories were used to evaluate the magnitude of these ES (small if $0.2 \leq d \leq 0.5$, medium if $0.5 < d \leq 0.8$ and large if $d > 0.8$) (Cohen 1988).

All results are expressed as the mean ± SD, except when otherwise specified. Statistical significance was fixed at $P \leq 0.05$ for all analyses.

RESULTS

Exercise parameters

Increases in HII_{ex} compared to MIC_{ex} were observed for mean heart rate (155 ± 16 vs 112 ± 14 , $P < 0.001$; ES = 2.49), intensity (71 ± 13 vs $42 \pm 9\%$ VO_{2max} , $P < 0.001$; ES = 2.67), and the rate of perceived exertion estimated by scores on the 6-to-20 Borg scale (15 ± 1 vs 11 ± 2 , $P < 0.001$; ES = 2.50). During the last HII_{ex} bouts, the scores were 17 ± 2 , showing that the exercise was perceived to be very hard. The intensity, heart rate, EE, and scores on Borg scale of the MIC_{ex} session were all consistent with the criteria of a moderate-intensity exercise (Norton et al. 2010).

As designed, there was no difference in the EE induced by the exercise trial between MIC_{ex} and HII_{ex} ($1,038 \pm 138$ vs $1,042 \pm 131$ kJ, respectively, $P = 0.876$; ES = -0.03). The RER was higher for HII_{ex} than MIC_{ex} (1.02 ± 0.05 vs 0.88 ± 0.03 , $P < 0.001$; ES = 2.84) due to an increase in carbohydrate oxidation (55.2 ± 10.6 vs 37.4 ± 9.0 g, $P < 0.001$; ES = 1.58) and a decrease in fat oxidation (2.0 ± 2.0 vs 10.0 ± 2.2 g $P < 0.001$; ES = -3.26) for HII_{ex} than MIC_{ex} .

Water intake at the end of the exercise trial was not significantly different between exercise conditions (162 ± 25 vs 144 ± 43 mL for HII_{ex} and MIC_{ex} , respectively, $P = 0.191$; ES = 0.45).

Metabolic parameters at the lunch request

At the lunch request, there was no effect of condition on EE or on RER.

Latency of lunch request

The mean and individual results are illustrated in Figure 2. There was a significant effect of condition on the latency of requesting lunch ($F(2,28) = 3.638$, $P = 0.039$). *Post-hoc* tests showed that the duration between the end of the exercise trials and lunch request

was longer for HII_{ex} than for REST (103.1 ± 20.9 vs 85.9 ± 17.5 min, $P = 0.004$; ES = 0.69), but not compared to that of MIC_{ex} (93.3 ± 24.6 min, $P = 0.686$; ES = 0.30). The difference between MIC_{ex} and REST was also non-significant ($P = 0.847$; ES = 0.30). Thus, participants requested their meal 17.3 ± 16.7 min later after the HII_{ex} than after REST. The duration between the end of exercise and the meal request was longer for HII_{ex} than REST for 11 of 15 participants, and it was more than 10 min for nine.

Appetite rating scales

Figure 3 displays the profiles of the four appetite scales. There were no significant differences between scores before the breakfast meal for any scale. There was no effect of condition or interaction between condition and time in the pre-trial profile for hunger, desire to eat, fullness, or prospective consumption. As the first request for lunch occurred at t180, the ANOVA was conducted between t120 and t180 for the post-trial appetite profile. There was a significant interaction between condition and time in the post-trial profile for hunger ($F(8,112) = 3.221$, $P = 0.003$) and desire to eat ($F(8,112) = 2.958$, $P = 0.005$). *Post-hoc* tests showed that at t180, hunger scores were lower after HII_{ex} (53.9 ± 20.6 mm) than after MIC_{ex} (69.6 ± 14.0 mm) and REST (65.3 ± 21.2 mm), but once corrected for multiple comparisons ($n=3$), these differences failed to reach significance ($P = 0.129$ and $P = 0.090$, respectively). A trend for similar differences in the desire to eat failed to reach significance (56.6 ± 21.2 in HII_{ex} versus 66.1 ± 19.8 after REST; $P = 0.268$ and versus 69.2 ± 14.5 after MIC_{ex}, $P = 0.270$). There was no effect of condition or interaction between condition and time for any of the two other scores or the four pre-lunch appetite profiles.

Energy and macronutrient intake at lunch

Figure 4 displays individual and mean EI at lunch and Table 2 the amount of food items consumed and macronutrient intake and percentages. There was no effect of condition on EI or the macronutrient composition of lunch. REI was consistently different between conditions ($F(2,28) = 5.383$, $P = 0.010$). *Post hoc* comparisons showed that REI was higher after REST (6728 ± 2391 kJ) than after HII_{ex} (5603 ± 1813 kJ, $P = 0.050$; ES = 0.46) and MIC_{ex} (5418 ± 1579 kJ, $P = 0.040$; ES = 0.62), but not different between MIC_{ex} and HII_{ex} ($P = 0.606$; ES = -0.16). However, inter-individual variability was large, with a continuous distribution of compensation, without any possible subdivision between compensators and non-compensators. Energy compensation was -47 ± 45 and $-24 \pm 42\%$ after MIC_{ex} and HII_{ex}, respectively ($P = 0.548$; ES = 0.11), showing that exercise-induced EE was not even partially compensated for either exercise condition.

Among food items, the only significant effect of condition was for biscuits ($F(2,28) = 4.298$, $P = 0.023$), with a greater amount of biscuits consumed after MIC_{ex} than after HII_{ex} (25 ± 16 and 16 ± 15 g, respectively, $P = 0.032$; ES = 0.49). Finally, water intake was influenced by condition ($F(2,28) = 3.606$, $P = 0.040$), with more water drank after HII_{ex} than after MIC_{ex} (413 ± 125 and 334 ± 134 ml, respectively, $P = 0.033$; ES = 0.49). Other comparisons between conditions were non-significant.

Liking of the foods

There was an effect of condition on liking of the main dish consumed at lunch ($F(2,28) = 4.349$, $P = 0.023$). Comparisons showed a tendency for a lower palatability of the main dish after HII_{ex} (77.4 ± 20.0 mm) than MIC_{ex} (85.4 ± 14.4 mm) and REST (87.9 ± 13.1 mm) but once corrected for multiple comparisons, these differences failed to reach

significance ($P = 0.147$ and $P = 0.115$, respectively). No other lining for other food items was modified by the condition and there was no difference in the global liking of the lunch between conditions.

Correlations

The differences in EI between each exercise session and REST were highly correlated ($r = 0.74$, $P = 0.002$), but not the differences in the latency of the meal request.

The differences in appetite ratings between each exercise session and REST at the end of each trial (t120) and at the meal request also strongly correlated for hunger ($r = 0.91$, $P < 0.001$ at t120 and $r = 0.77$, $P < 0.001$ at meal request), desire to eat ($r = 0.93$, $P < 0.001$ at t120 and $r = 0.63$, $P = 0.011$ at meal request), fullness ($r = 0.65$, $P = 0.008$ at t120 and $r = 0.86$, $P < 0.001$ at meal request), and prospective consumption ($r = 0.86$, $P < 0.001$ at t120 and $r = 0.89$, $P < 0.001$ at meal request).

DISCUSSION

This study shows that when participants are free to spontaneously initiate their meal, it occurs significantly later following 20 min of HII_{ex} compared to a rest session but not compared to MIC_{ex}. The delay of meal request after MIC_{ex} was not significantly increased compared to the rest session. The only difference in appetite was a trend for a lower hunger state 60 min after the end of the HII_{ex} trials than after the other sessions, whereas EI at the freely requested meal was not modified by any exercise modality. Thus, among the three components of eating behavior, the time factor was the most sensitive to the effect of HII_{ex} compared to rest.

The fact that the latency of the meal request was the main component of eating behavior significantly modified by HII_{ex} is not surprising. This variable has always been the most

sensitive to experimental interventions when included in eating behavior outcomes. For example, in a series of studies on the consequence of snacking on eating behavior, the latency of the meal request was altered but not appetite nor EI (Marmonier et al. 1999; Marmonier et al. 2000; Marmonier et al. 2002). Similar results were reported for pharmacological modification of fatty acid metabolism (Gatta et al. 2009). The few studies that allowed participants to spontaneously initiate eating after an exercise session also reported that the latency of meal initiation was the only component of eating behavior to be altered. A small (~5 min), but significant delayed eating onset was reported after continuous running or cycling exercises at moderate to vigorous intensity (70 to 77% $\text{VO}_{2\text{max}}$) for 26 to 60 min, depending on the procedures (King et al. 1994; King and Blundell 1995). This effect on latency to eat was however not found after low-intensity (~36% $\text{VO}_{2\text{max}}$) continuous exercises (King et al. 1994). This was associated with a very transient reduction in hunger immediately after the exercise trial, but without a change in EI. More recently, this result was confirmed with eating onset delayed by ~35 min after continuous running at 70% $\text{VO}_{2\text{max}}$ for 60 min (King et al. 2013). Again, there was no change in EI, and appetite was only less during and immediately after the exercise trial. In a previous study, we found a trend towards a delayed meal request (~14 min) after continuous cycling at 70% $\text{VO}_{2\text{max}}$ 75 min, but it failed to reach significance (Charlot et al. 2011). Thus, our results are consistent with these previous studies, the latency of meal initiation and not EI being the first component of eating behavior that is influenced by exercise. However, this result was observed only after HII_{ex} . As reported in King *et al.* (1994), MIC_{ex} had no effect on the latency of meal request, strongly suggesting that this effect requires at least a certain intensity (> 70% $\text{VO}_{2\text{max}}$) to be effective. The importance of such an intensity threshold

for exercise to delay the latency to eat has no definitive explanation. However, the biological determinants of intermeal intervals (Chapelot et al. 2000) highly suggest that this is mediated by the post-exercise increase in fatty acid oxidation (Krzentowski et al. 1982). With exercises matched in EE, this was actually reported at 70% but not at 35% $\text{VO}_{2\text{max}}$ (Pillard et al. 2010). This higher contribution of fat to metabolism may postpone the preprandial glucose decline (Campfield and Smith 2003), a meal-triggering phenomenon found even after exercise (Charlot et al. 2011).

The characteristics (intensity and duration) of our HII_{ex} were chosen to be close to those from similar studies (Sim et al. 2014; Shamlan et al. 2017) and to those successfully used to improve health risk factors (Gillen et al. 2011; Hood et al. 2011; Little et al. 2011; Currie et al. 2013; Esfandiari et al. 2014; Klonizakis et al. 2014). The HII_{ex} reached ~ 9.5 MET, with a score of 15.4 on the Borg scale, which can be classified as moderate to vigorous activity. We used 30-s high-intensity bouts because they are perceived to be less exhausting than those of 60 s (Kilpatrick and Greeley 2014) for a similar efficiency. This HII_{ex} modality is therefore appropriate for various populations. Here, we show that it significantly postponed eating onset. In order for matching EE across exercise conditions, the intensity (42% $\text{VO}_{2\text{max}}$) and energy expended ($\sim 1,100$ kJ) in the MIC_{ex} session were low compared to a standard continuous session. Therefore, results with the MIC_{ex} may not be relevant to a traditional recommended continuous exercise session. Meal request was delayed in three previous studies (King et al. 1994; King and Blundell 1995; King et al. 2013) using continuous exercise with intensities higher than 70% of $\text{VO}_{2\text{max}}$, durations longer than 26 min and EE higher than 1200 kJ. It seems therefore that intensity rather than EE of MIC_{ex} may have reduced the chances to postpone eating onset. This hypothesis also stands with hunger sensations. Indeed, it

was shown that intensities above 70 % of $\text{VO}_{2\text{max}}$ are required to transiently suppress hunger (King et al. 1994; King et al. 2010; Wasse et al. 2011; Deighton et al. 2012). Finally, concerning the last outcome EI, the characteristics of the MIC_{ex} were unlikely to be limiting factors. Indeed, in their review, Schubert *et al.* (2013) stated that exercise-induced EE and exercise intensity had no impact on the subsequent EI. We therefore conceded that the MIC_{ex} designed to match HII_{ex} -EE may have been insufficiently intense to postpone eating onset and suppress appetite.

When the meal time is fixed, and no snack is available or allowed, intake at the next planned eating occasion is another variable of eating behavior that may be altered by prior exercise. Under these conditions, the absence of accurate compensation of the exercise-induced EE is now well demonstrated (Broom et al. 2007; Burns et al. 2007; Elder and Roberts 2007; Schubert et al. 2013; Deighton and Stensel 2014). Our studies and those of others (King et al. 1994, King and Blundell 1995; King et al. 2013) confirm that when the time to eat can be freely chosen, there is no significant energy compensation at the next meal. This is all the more striking as longer latency enhances exercise-induced energy depletion. However, the individual results showed that, consistent with previous studies (Finlayson et al. 2009; Charlot and Chapelot 2013; King et al. 2013) there was a wide variability in EI and the latency to meal request. Figure 2 shows that there was not a dichotomous response after the HII_{ex} session, with responders and non-responders, similar to the compensators and non-compensators model (Finlayson et al. 2009) but a continuum as in one of our previous studies (Charlot and Chapelot 2013). Individual data also suggest that the MCI_{ex} session failed to delay the latency to eat due to 5 subjects displaying substantial longer latencies to eat following the rest than the exercise session. Studies are needed to determine whether

this reveals robust different physiological responses between sub-groups or results from day-to-day variations caused by uncontrolled experimental factors.

Interestingly, the individual EI and appetite responses to MIC_{ex} and HII_{ex} were highly correlated with each other, suggesting that participants' compensation for one exercise modality is indicative of their compensation for another. This finding, along with recent results showing that the compensation to the same exercise was reproducible (Unick et al. 2015), argues for the relevance of these experimental studies. It may also indicate whether someone is a strong compensator after exercise or not.

Overall, these results suggest that, although mealtimes are generally constrained by the social rules of everyday life, one of the first mechanisms of energy homeostasis i.e., the latency of eating onset, still operates, even after exercise (Davies 1977; Strubbe and van Dijk 2002). However, the expected response would be a shortened and not lengthened time before eating is initiated, and a higher, rather than unchanged or lower EI at the next meal, as exercise induces an energy deficit. This suggests that exercise triggers mechanisms that rely more on endogenous than exogenous energy substrates. Another perspective is to consider that our sedentary lifestyle leads to overeating. It was shown 50 years ago that animals adjust their EI to EE when they exercise, but show a paradoxical increased intake when they remain sedentary, leading to their being overweight and obesity (Mayer and Thomas 1967). This has been confirmed in humans, in particular children (Epstein et al. 2002) and adolescents (Epstein et al. 2005; Thivel et al. 2013). Whether exercise is followed by compensation of the energy expended or the control sedentary condition is followed by an increase in EI relative to energy needs is yet to be determined. In epidemiological studies, sedentary behavior is associated with

increased body weight and fat mass (Spanier et al. 2006), and eating behavior may contribute to this effect.

Our study has a certain number of limitations. First, indirect calorimetry accuracy tends to decrease with high intensities ($> 75\%$ of $\text{VO}_{2\text{max}}$) such as in the intense periods of HII_{ex} . The buffering of excess H^+ due to lactate accumulation increases VCO_2 and results in an overestimation of RER, CHO oxidation and EE (Jeukendrup and Wallis 2005). There is therefore a risk that EE is slightly overestimated in HII_{ex} . Second, the EE between the end of exercise (or rest) and eating onset was not measured, except for the EE at meal request. Our primary outcome was eating behavior and, notably, the latency to eat. We thus chose not to measure EE during this interval due to the unknown but potential interfering effect of this measure (in particular, wearing of a mask) on subjective parameters, such as appetite sensations and eating onset. It is to note that this difference in post-exercise expended energy is rarely if ever recorded in studies, even those not measuring the latency to eat. Compared to a MIC_{ex} session (Laforgia et al. 1997) or rest (Kelly et al. 2013), HII_{ex} induced only marginal excesses of EE in regard to the exercise-induced EE (up to 60 kJ) during the first hour of recovery. However, all conclusions about energy balance must be made with caution. Third, our results and conclusions are limited to young, healthy, active, and non-obese males. It will be necessary to study individuals with various characteristics in the future before generalization to wider populations. Last, the reliability of EI assessed in the laboratory is always questionable due to uncertain reproducibility. However, reproducibility has been found to be better for a main-dish meal, such as in the present study (Laan et al. 2011) than for a buffet-type meal (Brown et al. 2012).

The key finding of this study is that completing a standard HII_{ex} session in the morning increased the time before participants felt the need to consume their lunch compared to that following a resting session, without modifying EI during this meal. Appetite was consistently slower to reach its preprandial level. Conversely, completing a moderate-intensity continuous exercise matched for EE did not effectively modify any component of eating behavior. Inter-participant variability in energy compensation was large, as in previous studies, and precludes any conclusions at an individual level. However, the strong correlation of appetite responses and energy compensation between exercise modalities suggests that the individual response of eating behavior to exercise shows some stability across modalities.

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Conflict of Interest

The authors have no conflicts of interest to report.

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Tables

Table 1. Participants characteristics

Age (y)	20.1 ± 2.2
Weight (kg)	72.5 ± 13.5
Body mass index (kg m ⁻²)	23.5 ± 3.1
Body fat mass ^a (%)	15.0 ± 6.1
Restraint score ^b	13.5 ± 6.9
VO _{2max} (mL kg ⁻¹ min ⁻¹)	47.0 ± 12.2
Power at VO _{2max} (W)	229 ± 29
Maximal heart rate (bpm)	192.4 ± 7.2

Values are means ± SD (*n* = 15).

VO_{2max}: maximal oxygen uptake

^aBody fat estimated by bioimpedancemetry

^bRestraint score evaluated by the Three Factor Eating Questionnaire R-18

Table 2. Food item consumption at lunch and macronutrient intake

	REST	MIC _{ex}	HII _{ex}
Spaghetti bolognese			
g	639 ± 258	564 ± 134	623 ± 174
kJ	5 166 ± 2085	4 566 ± 1085	5 038 ± 1410
Bread			
g	63 ± 35	64 ± 39	71 ± 42
kJ	725 ± 405	733 ± 451	813 ± 483
Biscuits			
g	19 ± 16	25 ± 16 [†]	16 ± 15
kJ	343 ± 294	457 ± 300 [†]	297 ± 276
Stewed apples			
g	202 ± 143	189 ± 131	169 ± 90
kJ	742 ± 527	696 ± 481	621 ± 332
Carbohydrate			
g	257 ± 20	241 ± 16	248 ± 16
% of total EI	62.1 ± 3.6	62.0 ± 3.9	61.1 ± 3.1
Fat			
g	40 ± 4	36 ± 2	36 ± 2
% of total EI	21.0 ± 2.2	21.2 ± 2.3	21.4 ± 2.0
Protein			
g	71 ± 6	64 ± 4	70 ± 4
% of total EI	17.0 ± 1.5	16.8 ± 1.7	17.5 ± 1.2
Water (mL)	394 ± 140	334 ± 134 [†]	413 ± 125

Values are means $\pm$ SD. REST: resting condition; MIC_{ex}: moderate-intensity continuous exercise; HII_{ex}: high-intensity interval exercise; EI: energy intake. [†]Significantly different from HII_{ex}, $P < 0.05$ (exact values in the text).

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Figure legends

Figure 1. Schedule of the experimental procedure. VAS: Visual analog scale; MIC_{ex}: moderate-intensity continuous exercise; HII_{ex}: high-intensity interval exercise.

Figure 2. Latency of meal request. (A) Individual differences in latency between rest (REST) and moderate-intensity continuous exercise (MIC_{ex}) or high-intensity interval exercise (HII_{ex}). Positive results indicate that the latency of meal request after the exercise session exceeded that after REST. (B) Box-and-whisker plots for the latency of meal request for the three conditions. The box encompasses the 25%-75% quartiles and the median is represented by the horizontal line within the box. The whiskers extend to the highest and lowest values. Individual values are represented by dots. **Significantly different from REST, $P < 0.01$.

Figure 3. Appetite ratings of (A) hunger, (B) desire to eat, (C) fullness, and (D) prospective consumption scales. The anterograde profile from breakfast to 180 min (time at which the first participant requested his meal) (left) and the retrograde profile from meal request to the prior 45 min value (right) are shown for each scale. The black rectangle indicates breakfast and the grey rectangle the intervention (rest or exercise). The HII_{ex} session only lasted 20 min and thus the first 20 min consisted of resting. Values are shown as the means $\pm$ SEM ($n = 15$).

Figure 4. Energy compensation. (A) Individual differences in energy intake (EI) between rest (REST) and moderate-intensity continuous exercise (MIC_{ex}, white bars) or high-intensity interval exercise (HII_{ex}, black bars). Positive results indicate that the EI

after the exercise session exceeded that after REST, whereas negative results indicate that the negative energy balance was still higher relative to REST. Box-and-whisker plots for absolute (B) and relative (C) EI at lunch. The box encompasses the 25%-75% quartiles, and the median is represented by the horizontal line within the box. The whiskers extend to the highest and lowest values. Individual values are represented by dots. *Significantly different from REST, $P < 0.05$.

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Figure 1. Schedule of the experimental procedure. VAS: Visual analog scale; MICex: moderate-intensity continuous exercise; HIlex: high-intensity interval exercise.

89x38mm (300 x 300 DPI)

Figure 2. Latency of meal request. (A) Individual differences in latency between rest (REST) and moderate-intensity continuous exercise (MICex) or high-intensity interval exercise (HIIex). Positive results indicate that the latency of meal request after the exercise session exceeded that after REST. (B) Box-and-whisker plots for the latency of meal request for the three conditions. The box encompasses the 25%-75% quartiles and the median is represented by the horizontal line within the box. The whiskers extend to the highest and lowest values. Individual values are represented by dots. **Significantly different from REST, $P < 0.01$.

253x94mm (300 x 300 DPI)

Figure 3. Appetite ratings of (A) hunger, (B) desire to eat, (C) fullness, and (D) prospective consumption scales. The anterograde profile from breakfast to 180 min (time at which the first participant requested his meal) (left) and the retrograde profile from meal request to the prior 45 min value (right) are shown for each scale. The black rectangle indicates breakfast and the grey rectangle the intervention (rest or exercise). The HII_{ex} session only lasted 20 min and thus the first 20 min consisted of resting. Values are shown as the means $\pm$ SEM ($n = 15$).

419x219mm (186 x 186 DPI)

Figure 4. Energy compensation. (A) Individual differences in energy intake (EI) between rest (REST) and moderate-intensity continuous exercise (MIC_{ex}, white bars) or high-intensity interval exercise (HII_{ex}, black bars). Positive results indicate that the EI after the exercise session exceeded that after REST, whereas negative results indicate that the negative energy balance was still higher relative to REST. Box-and-whisker plots for absolute (A) and relative (B) EI at lunch. The box encompasses the 25%-75% quartiles, and the median is represented by the horizontal line within the box. The whiskers extend to the highest and lowest values. Individual values are represented by dots. *Significantly different from REST, $P < 0.001$.

189x142mm (300 x 300 DPI)

39x18mm (300 x 300 DPI)