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Beaulieu, K orcid.org/0000-0001-8926-6953, Hopkins, M orcid.org/0000-0002-7655-0215, Blundell, J orcid.org/0000-0002-7085-9596 et al. (1 more author) (2018) Homeostatic and non-homeostatic appetite control along the spectrum of physical activity levels: An updated perspective. Physiology and Behavior, 192. pp. 23-29. ISSN 0031-9384

https://doi.org/10.1016/j.physbeh.2017.12.032

Homeostatic and non-homeostatic appetite control along the spectrum of physical activity levels: an updated perspective

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Abstract

The current obesogenic environment promotes physical inactivity and food consumption in excess of energy requirements, two important modifiable risk factors influencing energy balance. Habitual physical activity has been shown to impact not only energy expenditure, but also energy intake through mechanisms of appetite control. This review summarizes recent theory and evidence underpinning the role of physical activity in the homeostatic and non-homeostatic mechanisms controlling appetite. Energy intake along the spectrum of physical activity levels (inactive to highly active) appears to be J-shaped, with low levels of physical activity leading to dysregulated appetite and a mismatch between energy intake and expenditure. At higher levels, habitual physical activity influences homeostatic appetite control in a dual-process action by increasing the drive to eat through greater energy expenditure, but also by enhancing post-meal satiety, allowing energy intake to better match energy expenditure in response to hunger and satiety signals. There is clear presumptive evidence that physical activity energy expenditure can act as a drive (determinant) of energy intake. The influence of physical activity level on non-homeostatic appetite control is less clear, but low levels of physical activity may amplify hedonic states and behavioural traits favouring overconsumption indirectly through increased body fat. More evidence is required to understand the interaction between physical activity, appetite control and diet composition on passive overconsumption and energy balance. Furthermore, potential moderators of appetite control along the spectrum of physical activity, such as body composition, sex, and type, intensity and timing of physical activity, remain to be fully understood.

Keywords: appetite control, physical activity, energy intake, food hedonics, energy balance

1. Defining energy balance and appetite control

Energy balance and resulting effects on body weight are the product of a complex relationship between energy intake (EI) and energy expenditure (EE). EI is modulated by the appetite control system through food consumption and eating behaviour. EI is largely influenced by a combination of internal biological factors such as resting metabolic rate (RMR) [1] and external nutritional factors such as energy density (kcal/g) of the food consumed [2], with intake being greater at higher RMR and energy density [3]. Of the macronutrients, dietary fat has the strongest influence on energy density (9 kcal/g) compared to carbohydrate and protein (4 kcal/g). Because of its higher energy density, dietary fat has been shown to be less satiating per unit of energy than the other macronutrients, resulting in greater energy intake when consumed ad libitum, which has led to the term “passive overconsumption” [4].

On the other side of the energy balance equation is EE, which is composed of RMR, physical activity energy expenditure (PAEE) and thermic effect of food (TEF), with typical ranges of 60-70%, 15-35% and 5-15% of total daily energy expenditure (TDEE), respectively [5]. PA encompasses structured exercise in addition to occupational, household, transportation and other activities of daily living, termed non-exercise activity thermogenesis (NEAT) [6]. In recent years, wearable technologies that estimate free-living total daily energy expenditure (TDEE), and minutes spent sedentary and in different intensities of PA (i.e. light, moderate and vigorous) have allowed for the objective assessment of habitual PA level, which was a major limitation of past research investigating the impact of habitual PA on appetite control [7]. These methods have also been improved to properly assess sedentary behaviour using inclinometers, which is specifically defined as “any waking behaviour characterized by an energy expenditure ≤1.5 metabolic equivalents (METs), while in a sitting, reclining or lying posture” [8]. This is different to physical inactivity which is “an insufficient physical activity level to meet present physical activity recommendations” [8]. Distinguishing between sedentary behaviour and physical inactivity is of importance to better understand their influence on

energy balance and appetite control. This review focuses on habitual PA levels (i.e. physical activity/inactivity) rather than sedentary behaviour.

The components of TDEE are illustrated in Figure 1, which shows the contribution of RMR and PAEE towards TDEE can vary widely between individuals depending on levels of PA. Indeed, within this group of 70 individuals (61% female, age: 29.5 ± 9.1 years, body mass index: 22.7 ± 2.3 kg/m^2; means ± SD) [9, 10], PAEE varied in absolute values between 102 and 1579 kcal, and from 5% to 43% as a percentage of TDEE. Our argument is that this degree of variability must have considerable implications for appetite control, energy balance and body weight. Here, PAEE was calculated by subtracting measured RMR (indirect calorimetry) and estimated TEF (~10% of TDEE) from measured TDEE obtained from a multi-sensor accelerometry device worn for five to seven days. While TEF was estimated at 10% as a generalisation for healthy individuals consuming a mixed diet, it is important to consider that TEF varies according to the energy content and macronutrient composition of food [11] and is perhaps reduced with obesity [12], but further well-designed studies are required to confirm the latter [11].

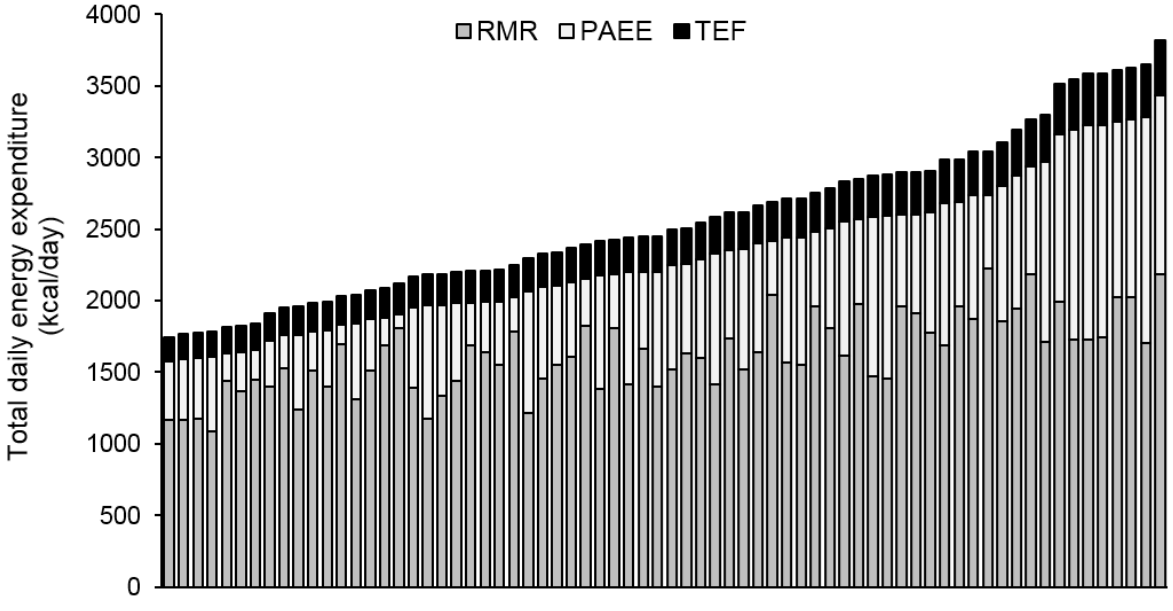


Figure 1 Individual profile (n=70) of the components of TDEE including resting metabolic rate (RMR), physical activity energy expenditure (PAEE), thermic effect of food (TEF). TDEE is

87 composed primarily of RMR, followed by PAEE, which varies widely between individuals. From
88 Beaulieu et al. [unpublished results].

89

90 In order to understand how PA influences appetite, it is necessary to have a
91 conceptualisation of the functional operations of the appetite system. Our position is that
92 appetite is controlled by several processes that form a psychobiological system that signals
93 hunger (drives feeding), satiation (terminates feeding) and satiety (post-meal suppression of
94 hunger), which in turn determine food (energy) intake [13]. These processes are influenced
95 by episodic and tonic signals. Episodic signals occur on a meal-to-meal basis and diurnal
96 variations in these signals reflect the size, pattern and frequency of meals and eating
97 episodes. Episodic signals can be excitatory or inhibitory, and are related to meal initiation,
98 termination and satiety. Tonic signals stem from body tissues and cellular metabolism, and
99 convey information relating to energy availability and energy needs to the central nervous
100 system [14]. These homeostatic mechanisms interact with non-homeostatic processes, such
101 as food hedonics and behavioural traits, in the overall expression of appetite [15]. The complex
102 relationships between homeostatic and non-homeostatic inputs, coupled with the current
103 obesogenic food environment, can make individuals vulnerable to overconsumption and
104 weight gain. However, there has been increasing interest and research on the influence and
105 benefits of PA on appetite control as it plays an integral (and readily modifiable) part in energy
106 balance and body weight [16-20]. The aim of this review is to summarize recent theory and
107 evidence underpinning the role of habitual PA in the mechanisms controlling appetite and its
108 impact on energy balance. In principle, PA could influence tonic and episodic appetite control
109 by adjusting the biological components of fat-free mass, fat mass, RMR and postprandial
110 peptides, for example. In addition, our position is that PA will influence appetite control via
111 both direct and indirect mechanisms; the direct effect of PAEE will drive appetite in a similar
112 manner to RMR, i.e. by increasing TDEE and associated energy demand.

1.1 A note on physical activity, energy expenditure and body composition

Common beliefs regarding TDEE assume that it increases linearly with PA in a dose-dependent manner, whereby greater PA levels lead to greater TDEE [21]. Recently, whether TDEE increases in proportion to PA level has been debated, and a constrained EE model has been proposed by Pontzer et al. [22]. Using doubly-labelled water to measure TDEE and accelerometers to measure PA in several populations of adults, these authors demonstrated that at lower levels of PA, TDEE increases linearly with PA, but at a certain threshold of much higher PA, there was a plateau in TDEE. Thus, it was suggested that TDEE is regulated such that compensatory reductions in other metabolic processes or components of TDEE occur with increasing PA to maintain TDEE within a certain narrow range [22]. This could be related to a reduction in NEAT or enhanced metabolic economy/efficiency of PA at higher levels of PA. However, further evidence is required to validate this model, and more convincing study designs are needed to elucidate the mechanisms that could regulate TDEE and the specific components of TDEE affected at very high levels of PA.

It is also important to emphasise that within the general population, which is highly inactive and at the low end of the PA spectrum [23], an increase in PA will likely lead to an increase in TDEE. Therefore, PA should remain a key component in weight management and health promotion for everyone.[1] Indeed, data from our group have shown significant inverse associations between objectively-measured PA and adiposity in individuals ranging in body mass index [24] as well as a significant body fat loss in response to a 12-week exercise intervention in inactive men and women with overweight and obesity [25], in line with systematic reviews [26, 27].

[1] It should be kept in mind that some studies have shown unchanged TDEE despite increased PAEE in certain inactive populations; see Melanson [21] for review.

2. Homeostatic mechanisms of appetite control

The homeostatic control of appetite can be conceptualised as a matrix of events and interactions occurring in the three levels of the psychobiological system. These include psychological and behavioural events, peripheral physiological and metabolic events, and neurotransmitter and metabolic interactions in the brain [13]. It has been argued that the desynchronisation of these three levels is associated with a disruption of appetite, for example with eating disorders (and perhaps with physical inactivity and obesity). The system incorporates the events and behaviours that lead to, arise during, terminate and occur after food consumption, which have been termed the Satiety Cascade [13]. During and shortly after food intake and gastric emptying, the secretion of the orexigenic (appetite stimulating) peptide ghrelin is suppressed and a variety of anorectic (appetite inhibiting) peptides, such as cholecystokinin (CCK), glucagon-like peptide 1 (GLP-1), and peptide YY (PYY), among others, are released from the gut to promote meal termination (satiation) and the post-meal suppression of hunger (satiety), which in turn, coordinate meal size and frequency [13, 28, 29]. In addition to its episodic role, ghrelin may also be involved in tonic appetite control as a compensatory hormone to restore body weight status; with obesity, ghrelin concentrations appear to be lower, whereas with weight loss, they increase [30]. Other tonic signals such as leptin and insulin have been hypothesised to act directly in the central nervous system to reduce appetite and energy intake [31]. However, with body fat accumulation there appears to be a resistance to the direct negative feedback action of leptin and insulin in the hypothalamus [14, 31]. Moreover, it is believed that an interaction between episodic and tonic peptides exists, with a reduced sensitivity to leptin or insulin with increased body fat leading to blunted signalling of satiety peptides such as CCK and GLP-1 [14, 32, 33]. Indeed, the postprandial response of insulin has been associated with satiety in lean individuals, but not in individuals with obesity [32, 34-37].

3. Non-homeostatic factors involved in appetite control and eating behaviour

In addition to homeostatic mechanisms, non-homeostatic factors involved in appetite control include food hedonics and eating behaviour traits [38, 39]. Hedonic thoughts about food and the sensory appreciation of certain food attributes like salt, sugar and fat determine food preference and choice, and thereby contribute to meal size and frequency [40]. Food hedonics reflect the separate processes of 'liking' and 'wanting' [41]. Liking can be defined as the degree of sensory pleasure obtained from foods, whereas wanting is the motivation or attraction towards certain foods [42]. While both processes are involved in the motivation to eat, they operate as distinct entities where an increase in wanting may not necessarily predict an increase in liking and vice versa [43]. Wanting may be more important for overconsumption and maintenance of obesity than liking, which tends to remain stable within an individual and does not appear to be influenced by obesity [39, 40, 44]. Eating behaviour traits such as dietary restraint (i.e. concern over weight gain and the attempt to reduce food intake), disinhibition (i.e. tendency of an individual to overeat and to eat opportunistically in the obesogenic environment) [45], binge eating (i.e. excessive consumption of food in a discrete period of time often accompanied by feelings of guilt and loss of control over eating) [46] and control over food cravings (i.e. frequency, intensity and type of food cravings) [47] are also considered as risk factors for overconsumption and weight gain [48].

In today's obesogenic environment, the availability of highly palatable and often energy-dense foods raises the importance of hedonic influences on the control of food intake that occur independently from and/or in opposition to the energy need or weight status of an individual [49]. Indeed, there is growing evidence to support the considerable functional overlap between the homeostatic and hedonic mechanisms of appetite control [15, 50], which could be linked by GLP-1 [51], ghrelin [52, 53], insulin and/or leptin [14]. Consequently, hedonic signals occurring when palatable and energy-dense foods are ingested can disrupt or override homeostatic satiety signals and lead to overconsumption [52]. Indeed, it has been suggested that chronic high-fat intake attenuates the satiating properties of CCK through reduced sensitivity of the vagal receptors [54, 55]. Moreover, it appears the PYY response to

dietary fat is attenuated in individuals with obesity compared to those with a healthy weight [56]. This may be mediated by an accumulation of body fat which has been proposed to weaken satiety signalling [14, 32, 33], perpetuating overeating in individuals with excess body fat and obesity. However, it is important to note that palatability of food per se may not lead to overconsumption but is it rather the high energy density associated with palatable foods rich in fat and sugar that is driving the increase in EI [39]. For example, consumption of highly palatable artificially sweetened low-calorie foods may not cause overconsumption of energy at a particular meal (but some studies have shown that consuming artificial sweeteners can lead to overconsumption at subsequent meals [57]).

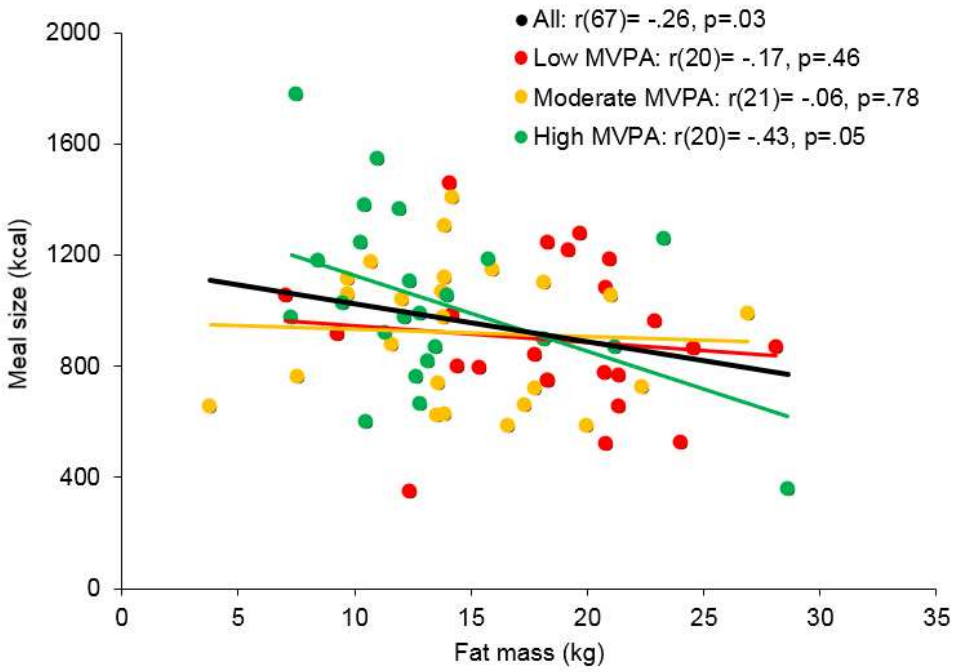
4. Energy intake and appetite control along the spectrum of physical activity levels

While there is evidence for the negative feedback mechanisms involved in satiation and satiety based on the interaction between tonic adiposity and episodic gut signals, less is known on the factors that drive hunger and food intake. Whether EE and PA are drivers of EI has not been well understood [58]. The relationship between EE, PA and EI in humans was examined over 50 years ago [59-61]. Mayer et al. demonstrated a relationship between occupational PA and daily EI in Bengali jute mill workers whose daily occupations ranged from "sedentary" to "very heavy work" whereby those performing very heavy work consumed more than those performing light work [61]. In line with Mayer, Edholm et al. [60] found a strong relationship between TDEE and daily EI in army cadets over three weeks. Despite providing initial evidence for physiological processes and behavioural activities impacting on appetite and providing a demand for food intake, this concept was left dormant for several decades.

The roles of body composition and EE in driving food intake have recently been re-examined and have gathered attention within the scientific community [62, 63]. Fat-free mass has been found to be strongly positively associated with EI in lean and overweight/obese individuals [64, 65], corroborating findings from earlier but less known studies [66, 67]. In

contrast, an inverse relationship between fat mass and EI, and hunger and EI was found in lean but these associations were weaker and less consistent in overweight and obese individuals [64, 66-68]. These findings are in line with the proposition that negative feedback signals reflecting energy stores inhibiting food intake are blunted with higher body fat [14, 31]. In addition to fat-free mass, RMR has also been shown to predict EI and hunger [1], which led to the suggestion that RMR (largely determined by fat-free mass) exerts a tonic day-to-day signal for hunger and the drive to eat [69]. It has recently been shown that the associations between fat-free mass and EI are mediated by RMR [3] and TDEE [70], suggesting that the associations between fat-free mass and EI reflect the energetic demands of metabolically active tissue.

In the 70 individuals from Figure 1, we found that both fat-free mass and fat mass were significantly positively and inversely associated with meal size, respectively, corroborating prior studies in lean individuals [62, 66]. Interestingly, exploratory analyses suggested that the strength of the association between fat mass and meal size may be moderated by PA level as the association was strongest in those with the highest time spent in moderate-to-vigorous PA (MVPA) when divided by sex-stratified tertiles (Figure 2) [Beaulieu et al., unpublished results]. However, the mechanisms responsible for this effect are unknown and whether these stem from a direct effect of PA on fat mass or indirectly though other physiological, behavioural or psychological factors remains to be elucidated.



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237 **Figure 2** Relationship between fat mass and meal size within sex-stratified tertiles of
238 moderate-to-vigorous PA (MVPA; n=70). The strength of the inverse association between fat
239 mass and energy intake was found to be strongest in those with the highest levels of PA.
240 From Beaulieu et al. [unpublished results].

241

242 The contribution of PA per se towards the drive to eat is less apparent. In comparison
243 to RMR, PAEE makes up a smaller portion of TDEE and is more variable; therefore, its impact
244 on EI may be harder to quantify. However, it can be proposed that PAEE (behavioural EE) will
245 be a determinant of EI just like RMR (but weaker overall and with great individual variability –
246 see Figure 1). Recently, a systematic review and a meta-analysis concluded that there is little
247 evidence that PA or exercise, whether acute or chronic, leads to changes in EI [71, 72].
248 However, the acute or relatively short-term nature of these studies may not have been long
249 enough to demonstrate a compensatory rise in EI with habitual PA [73] and as originally
250 demonstrated by Mayer et al. [61]. Indeed, a strong relationship was found between

objectively-measured PA (activity counts) and EI (food records) in 300 middle-aged women [74]. It is important to note that the study by Mayer et al. revealed two separate effects of habitual PA level on EI, characterised by a J-shape relationship. In the jute mill workers with higher levels of occupational PA (e.g. “medium” to “very heavy” work), daily EE and EI were closely matched, but at low levels of occupational PA where body mass was also greater, this coupling was lost, such that daily EI exceeded EE in those performing “sedentary” to “light” work [61].

4.1 The zones of appetite control

Based on the study by Mayer et al. [61], Blundell proposed that appetite control is enhanced with increasing levels of PA [75]. In contrast, physical inactivity could not only reduce TDEE but also lead to appetite dysregulation, overconsumption and eventually weight gain [75]. Indeed, according to Jacobs [76], “the late Henry L Taylor favoured a model that linked EI to EE in a J-shaped curve (personal communication, late 1970s). The first part of his concept was that EI is in exact homeostasis with EE under conditions of high EE. The second part was that there is a failure of homeostasis in a sedentary lifestyle because of its accompanying low EE. He postulated that body signals go awry in sedentary lifestyles; when a person does no physical work, the body will not recognize that it is being overfed. Sedentary persons may lose the innate ability to compensate for inactivity by reducing their eating” (p.189). It is important to note here that “sedentary” lifestyles used by this author should in fact be interpreted as inactive lifestyle in light of current definitions. Thus, Blundell revisited the Mayer J-shaped curve and suggested that individuals with low levels of PA could be considered as being within a “non-regulated zone” of appetite control, whereas those with higher levels of PA could be within a “regulated zone” of appetite control [75].

While this model of appetite control and EI along the spectrum of PA levels was originally based on limited evidence, it has recently been supported [7, 77]. In a systematic

277 review using data from 10 cross-sectional studies that compared EI in active and inactive
278 individuals, we plotted standardized EI (z-scores) according to four PA levels ranging from low
279 to very high. This analysis revealed a clear J-shape relationship between PA level and EI [7].
280 Similarly, Shook et al. estimated EI based on changes in body composition across quintiles of
281 PA in a large sample of young adults and again demonstrated appetite dysregulation in those
282 with the lowest PA [77].

283

284 **5. The impact of physical activity and exercise on the mechanisms of appetite control**

285 Emerging studies are shedding light on the mechanisms contributing to the proposed
286 dysregulation of appetite at lower levels of PA and more sensitive appetite control at higher
287 levels of PA. These mechanisms may not necessarily be the same along the whole spectrum
288 of PA levels. Acutely, exercise has been shown to influence gastric emptying [78], attenuate
289 the release of ghrelin and increase the secretion of PYY, GLP-1 and pancreatic polypeptide
290 [79]. Chronic exercise may increase the postprandial secretion of GLP-1 and PYY [80].
291 Therefore, habitual PA (and exercise) may interact with food intake to enhance hormonal
292 satiety signalling [81]. Moreover, regular PA and exercise training are associated with several
293 other physiological adaptations such as improved sensitivity to insulin [82] and leptin [83, 84],
294 substrate metabolism [85], and body composition [86], which have been proposed as
295 mechanisms involved in food intake and eating behaviour [87, 88]. Evidence suggests that PA
296 influences appetite control through a dual-process action which increases the drive to eat but
297 also post-meal satiety [89]. Several studies have now demonstrated that physically active
298 individuals show better energy compensation than their less active counterparts following
299 consumption of preloads differing in energy content such that they reduce EI to offset the
300 difference in energy consumed from the preloads [10, 90-94]. This preload-test meal paradigm
301 is effective in measuring the strength of satiety [95]. These improvements in satiety may be
302 associated with exercise-induced adaptations in episodic satiety signalling [80, 91, 96] or
303 gastric emptying [97]. In contrast, we have shown that satiation does not appear to be

304 influenced by PA level in non-obese individuals when measured with a passive
305 overconsumption paradigm comparing ad libitum EI at meals high in fat or carbohydrate [9].
306 However, in overweight and obese individuals, Caudwell et al. [1] showed that exercise
307 training led to a reduction in EI at a high-fat/energy dense test meal. This may be associated
308 with enhanced satiation, but given the homeostatic and non-homeostatic determinants of food
309 intake, may also reflect changes in food hedonics or behavioural traits.

310 While there is strong support that habitual PA affects homeostatic mechanisms
311 controlling food intake, less is known on its effect on non-homeostatic processes, and their
312 contribution to appetite control along the spectrum of PA levels. Indeed, secondary analyses
313 from the study from Caudwell et al. [1] revealed a reduction in hedonic wanting for high-fat
314 foods relative to low-fat foods (Leeds Food Preference Questionnaire), disinhibition and binge
315 eating following exercise training [Beaulieu et al., unpublished results]. Furthermore, another
316 study from our group found inverse associations between time spent in MVPA and disinhibition
317 and binge eating, but these did not remain significant after controlling for body fat [24]. This
318 corroborates a study by Shook et al. who found greater disinhibition in their lowest quintile of
319 MVPA but not when controlling for body weight [77], and the aforementioned reduction in
320 disinhibition and binge eating score following 12 weeks of exercise training which did not
321 remain significant after controlling for change in body fat [Beaulieu et al., unpublished results].
322 These differences in disinhibition and binge eating were not apparent in non-obese individuals
323 varying in PA levels [9, 10], suggesting the influence of habitual PA on eating behaviour traits
324 may be more strongly influenced by body composition. In terms of food hedonics, differences
325 in the rewarding value of foods (liking and wanting) have been observed in lean active
326 compared to overweight inactive males [98], but in non-obese individuals, PA level did not
327 influence liking and wanting for high-fat food in the hungry or fed states [9, 10]. In inactive
328 individuals with overweight and obesity, 12 weeks of exercise training (125-250 kcal per
329 exercise session) did not affect liking or wanting [99], whereas another 12-week intervention
330 at a higher dose of exercise (500 kcal per exercise session) reduced the hedonic wanting for

high-fat food independent of changes in body fat [Beaulieu et al. unpublished results]. Moreover, habitual (self-reported) PA may differently impact food cravings depending on exercise type and sex [100]. These studies suggest there may be differing effects of PA on non-homeostatic appetite control according to an individual's body fat status, sex, and dose and type of PA.

Therefore, we can propose that in addition to individuals with non-regulated appetite having blunted satiety signalling, excess body fat in these individuals may amplify non-homeostatic inputs favouring overconsumption. In contrast, individuals with regulated appetite with higher levels of PA have enhanced postprandial sensitivity, allowing for EI to be better matched to EE in response to hunger and satiety signals. This is demonstrated in an updated perspective of the zones of appetite control in Figure 3.

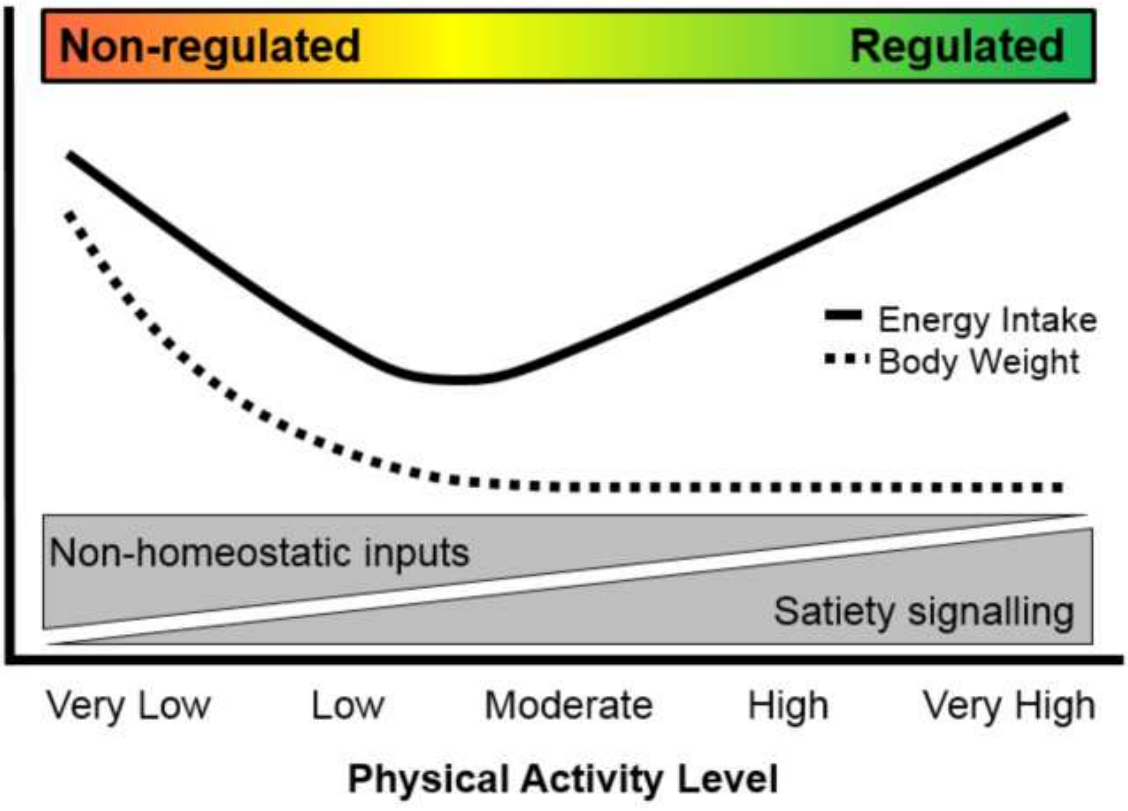

Figure 3 An updated perspective of appetite control along the spectrum of PA levels based on the study by Mayer et al. [61] and Blundell [75]. Individuals with non-regulated appetite have lower levels of PA, higher body fat, greater non-homeostatic influences favouring

346 overconsumption and weaker satiety response to food. Those with regulated appetite have
347 higher levels of PA, lower body fat, increased drive to eat and enhanced satiety response to
348 food.

349

350 **6. Interaction between physical activity and diet composition on energy intake and**
351 **energy balance**

352 While PA appears to affect several mechanisms of appetite control, as described
353 above, whether it renders individuals less susceptible to overconsumption in the current
354 obesogenic food environment has not been extensively examined. This is important to
355 consider, with headlines stating “You cannot outrun a bad diet” [101]. Only a few studies have
356 investigated the impact of PA and diet composition on EI and energy balance. A study by
357 Tremblay et al. [102] in males found that consumption of a high-fat diet over two days following
358 a 500-kcal exercise bout led to a positive energy balance, whereas consumption of a low-fat
359 diet was able to maintain the energy deficit produced by exercise. Along those lines,
360 Murgatroyd et al. [103] showed in males that increasing the dietary fat content (and energy
361 density) of an ad libitum diet in a day where exercise was imposed (~675 kcal) increased EI
362 and led to a positive energy balance (albeit not statistically significant). Moreover, consumption
363 of a high-fat diet while imposing inactivity resulted in a daily positive energy balance of
364 approximately 1000 kcal more than with imposed exercise, and 1200 kcal more than with
365 exercise on a low-fat diet. Other studies in males [104] and females [105] corroborated these
366 findings by demonstrating that the consumption of a high-fat meal following an exercise bout
367 resulted in significantly greater relative EI (after considering the EE of the exercise) compared
368 with a low-fat meal. Interestingly, palatability of both high-fat and low-fat meals increased after
369 exercise compared to rest in females, but not in males [105]. These studies highlight the
370 potency of the phenomenon of passive overconsumption. Therefore, the degree of
371 compensation observed in response to PAEE can readily be modulated simply by altering the
372 energy density of the diet and proposals about compensation need to be interpreted with care.

Whether being habitually physically active enhances the response to dietary manipulations is also of interest. As discussed above, we have shown that physically active individuals are also prone to acute passive overconsumption with an imposed high-fat meal [9]. In addition, while individuals with higher levels of PA were found to be sensitive to the acute nutritional manipulation of preloads varying in energy content by reducing EI at the following meal, objectively-measured daily EI (including the preload) was greater after a high-energy relative to a low-energy preload regardless of PA level, demonstrating an effect of passive overconsumption [10]. Others have shown that active individuals may compensate beyond the immediate meal following intake of a high-energy preload, attenuating the risk of overconsumption, but this was measured with food records and daily EI including the preload was not reported [90, 91, 93]. The long-term compensatory response to high energy density food consumption in physically active individuals is unknown. The EE associated with PA may be helpful in mitigating episodes of overconsumption and fluctuations in EI over time [106, 107]. However, given the available evidence, in the general population, higher levels of habitual PA in conjunction with a diet lower in energy density appear to be optimal for appetite control and energy balance.

7. Implications and future directions

The impact of PA on the mechanisms of appetite control has implications for individuals wishing to lose fat mass through exercise as large variability in the individual response to exercise interventions have been observed [89, 108]. These varying responses in fat loss to exercise training suggest that some individuals compensate for the increase in PA (and EE) through greater food intake or other mechanisms impacting on energy balance, minimizing the effect of exercise on fat loss. In both those susceptible and resistant to exercise-induced weight loss, hunger and the strength of satiety were enhanced with exercise training, showing a robust effect of the dual-process action of PA on appetite control; however, the increase in

hunger was greater in those resistant to weight loss [89]. The compensatory adaptations in appetite control and eating behaviour following exercise-induced weight loss are beyond the scope of this review and have been reviewed elsewhere [20, 109, 110]. Nevertheless, it should be acknowledged that certain baseline (pre-intervention) characteristics of appetite may predict the susceptibility to exercise-induced weight loss such as the hedonic response to acute exercise [111] and the peptide response to food consumption [112], which is of interest for future research to help personalise interventions to promote successful fat loss with exercise.

The role of PAEE in driving EI is important for future research to clarify as it can make up a significant proportion of TDEE in physically active individuals (see Figure 1) [113]. While the influence of PA on some processes of appetite appear to be independent of body fat, more research is required to understand the role of body composition and body fat status in the relationship between PA level and appetite control. We have reported above that PA (or factors associated with PA) may moderate the relationship between fat mass and EI, which is an interesting avenue for future research. Other potential moderators of the relationship between PA and appetite that remain to be examined further include sex [114] and age [93]. Additionally, very little is known on how the type, dose, intensity and timing of habitual PA and exercise affect homeostatic and non-homeostatic appetite. The mechanisms responsible for the apparent enhancement in the satiety response to food consumption in physically active individuals also remain to be fully elucidated. Finally, in light of the research on the interaction between PA and dietary manipulations, it is important for future research to take an energy balance perspective [115] to increase our understanding of the complex relationships and interactions among PA, diet composition, body composition and appetite control along the spectrum of PA levels.

8. Summary

Food intake is modulated by several homeostatic and non-homeostatic mechanisms controlling appetite. Evidence is accumulating to support the view that EI along the spectrum of PA is J-shaped, with individuals with low levels of PA being in a non-regulated zone of appetite whereas those with higher levels of PA operating in a regulated zone with more sensitive appetite control. Body fat also varies along the spectrum of PA and may impact the sensitivity of satiety signals and non-homeostatic inputs (food hedonics and behavioural traits) favouring overconsumption at lower levels of PA, but this remains to be fully understood. PA affects the homeostatic mechanisms of appetite via a proposed dual-process action of increased drive to eat from greater EE, but also by enhanced satiety response to food, likely through more sensitive postprandial signalling. An important tenet of our current position is that PAEE is a determinant of EI (although with greater variability than RMR). These processes generate a better adjustment of EI to EE in response to hunger and satiety signals at higher levels of PA. However, special attention needs to be given to diet composition, with a high-fat energy-dense diet leading to acute passive overconsumption of energy along the entire spectrum of PA. Importantly, the strength of the various mechanisms and determinants of appetite will vary between individuals along the spectrum of PA, highlighting the need to recognise that the impact of PA on appetite control is not a case of 'one size fits all'.

Conflict of interest

The authors declare no conflicts of interest.

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