The Impact of Physical Activity on Food Reward: Review and Conceptual Synthesis of Evidence from Observational, Acute, and Chronic Exercise Training Studies

Kristine Beaulieu1 · Pauline Oustric1 · Graham Finlayson1

Abstract
Purpose of Review This review brings together current evidence from observational, acute, and chronic exercise training studies to inform public debate on the impact of physical activity and exercise on food reward.

Recent Findings Low levels of physical activity are associated with higher liking and wanting for high-energy food. Acute bouts of exercise tend to reduce behavioral indices of reward for high-energy food in inactive individuals. A dissociation in liking (increase) and wanting (decrease) may occur during chronic exercise training associated with loss of body fat. Habitual moderate-to-vigorous physical activity is associated with lower liking and wanting for high-fat food, and higher liking for low-fat food.

Summary Food reward does not counteract the benefit of increasing physical activity levels for obesity management. Exercise training appears to be accompanied by positive changes in food preferences in line with an overall improvement in appetite control.

Keywords Physical activity · Exercise · Food reward · Appetite · Liking and wanting · Obesity management

Introduction
Among the reasons that people with obesity cite for avoiding exercise is a lack of enjoyment and perceived failure to lose weight [1, 2]. Moreover, there is a misconception that persists among some individuals that exercise is counter-productive for weight management. This common assertion is reinforced by occasional reports in the media about exercise and food reward [3, 4]. Biological explanations, reliant on soft evidence, have been put forward suggesting that glycogen depletion, reduced blood glucose levels, endorphin release or other signals generated during exercise can increase appetite or cause specific cravings for foods. Alternatively, psychological accounts propose that high fat or sugary foods are sought out post-exercise to counteract negative affect or reward virtuous behavior. Research over the past 10 years has shown that physical activity and eating behavior are loosely coupled, but the physiological and neurocognitive mechanisms that contribute to this relationship are complex [5]. Moreover, the evidence for the impact of physical activity on food reward is difficult to assess due to the absence of randomized controlled trials and differences between study designs—encompassing observational, acute, and chronic interventions. Differences also exist in the modality and intensity of physical activity examined and the variety of methodologies used to measure reward responses to food. In a review of longitudinal weight management interventions that measured food reward outcomes at baseline and follow-up, Oustric and colleagues [6] identified 17 studies consisting of dietary, pharmacological, cognitive, and exercise-based intervention types. Overall, a post-intervention reduction in food reward was found across all treatment types—except exercise, where no consistent changes were reported. While it is interesting to speculate that exercise training may have a moderating influence on the relationship between weight management and food reward, only three exercise studies were eligible for inclusion in this systematic review. Moreover, interpretation was limited by small sample sizes, lack of a control condition in one study, and inconsistent use of food reward measures. Further research is needed to update and summarize the available
Current Thinking on the Role of Physical Activity in Appetite Control

In the last 5 years, evidence has accrued showing that physical activity affects both episodic (meal-to-meal) and tonic (basal) homeostatic mechanisms that influence appetite control [7]. Acute exercise influences gastric emptying [8], and attenuates the release of ghrelin and increases the secretion of satiety peptides, e.g., peptide YY, glucagon-like peptide-1, and pancreatic polypeptide [9]. Chronic exercise improves body composition [10–12], and leptin and insulin sensitivity [13–15].

Our research has shown that habitual physical activity has a small positive association with daily energy intake (accounting for around ~3% of the variance) [16], but this is only logical when considering the increase in energy requirements and the longer-term indirect effects from increased resting metabolic rate after changes in fat-free mass. It has been proposed that chronic exercise influences appetite control through an increase in hunger but also a strengthening of post-meal satiety [17]. Indeed, exercise and physical activity appear to interact with nutritional factors to enhance satiety signaling, with studies showing that people who engaged in more exercise and physical activity were better able to compensate for differences in the energy content of food (achieved by increasing the ratio of fat to carbohydrate) at a subsequent meal than their less active counterparts [18]. While more active individuals are driven to eat more due to their greater energy requirements, their stronger satiety response to food appears to allow for a better matching between energy intake and energy expenditure [19••]. This relationship between physical activity level and daily energy intake is best represented by a J-shaped curve, whereby individuals with low levels of physical activity on the left of the curve have dysregulated appetite with greater intake than expenditure, and individuals with greater levels of physical activity towards the right of the curve have a proportional increase in intake with increasing expenditure. These findings suggest that concerns about exercise or increased levels of physical activity being counterproductive for obesity management should be concerned with non-homeostatic and food reward-related mechanisms that may be driving unhealthy food choices.

Defining Food Reward and Its Importance for Weight Management

Food reward is important for understanding appetite control and has the logical status of an intervening variable that guides eating behavior. Food reward is encoded by distinct neural pathways in the brain and can be modulated by metabolic signaling, sensory stimuli from the food environment and cognitive processes such as attention, learning, and memory [20]. Food reward is often conceptualized to consist of two distinct sub-components—“liking” and “wanting.” These have been broadly studied [21], following extensive work demonstrating their dissociation in the brain and behavior of many species including humans [22]. Liking is the sensory pleasure exerted while eating a food and wanting is rather the, often implicit, drive to eat triggered by a food cue [23]. Liking and implicit wanting for energy-dense foods are related to excess energy intake in free-living and laboratory settings [23, 24]. However, liking accounts only for a small proportion of the variance in food intake [25, 26], and unconscious processes such as implicit wanting may play a larger role in driving overeating [27, 28]. Food reward is an important factor in weight management through its intervening status between the nutritional requirements of the body and stimulation from the food environment [23], but it is likely that liking and implicit wanting sometimes act separately to influence appetite control [6••].

While several techniques to measure food reward have been developed [21] (e.g., reinforcing value tasks, willingness to pay), the Leeds Food Preference Questionnaire (LFPQ) has been designed to measure both liking and implicit wanting for distinct dimensions (e.g., fat and sweet taste) of foods common in the diet. Food reward measured by the LFPQ can be interpreted as both a state- and a trait-dependent measure depending on the timing and condition of measurement. Indeed, liking and wanting have been shown to be partially dissociable pre to post food consumption according to sensory-specific satiety [29]. On the contrary, food cravings, defined here as spontaneous instances of strong explicit wanting for a specific food, tend to be measured as a trait reflecting the frequency, intensity or quality of cravings experienced over a specified time period [30–32]. Neural activation to foods measured through functional magnetic resonance imaging (fMRI) are also used as an inference of food reward and this technique allows the analysis of different regions of interest and their functional connectivity [33]. However, fMRI measures of reward should be used in conjunction with behavioral measures or actual food intake to support their interpretation.
Review of Literature

Methods

The inclusion and exclusion criteria for this non-systematic review were established prospectively. We included studies with a general, healthy population of adults (≥18 years) or children (<18 years), including those with overweight or obesity. Studies that included adults or children with overweight or obesity who were specifically trying to lose weight were also included. We excluded studies in populations with diseases (including substance related and addictive disorders), in vitro and animal studies. The interventions and comparisons of interest included any type of structured exercise or comparisons between different physical activity levels. All chronic training studies had to have a minimum intervention duration of 4 weeks. The outcomes of interest included all psychometric measures of food reward obtained either directly (e.g., ratings or pleasantness or desire to eat) or indirectly (e.g., measure of the willingness to work to obtain a food, reaction time), as well as neuronal response to food cues measured by fMRI. We included unpublished and ongoing studies where relevant.

The search strategy for this review combined electronic searches and hand searching. To identify ongoing or completed, but unpublished trials, ClinicalTrials.gov was searched on 22 November 2019 and researchers known to be active in the topic were contacted. Limits were set to include all papers published in English or French after 2009, in healthy human samples. Authors were contacted for additional information if unclear or not reported in the manuscript.

Observational Studies of Physical Activity and Exercise

As shown in Table 1, only three studies have examined food reward differences in defined active and inactive groups [34, 35, 38]. Horner et al. [38] found that in the fed state, overall liking, and liking for high-fat savory, high-fat sweet, and low-fat sweet food measured by the LFPQ was lower in active compared with inactive men differing in BMI, and differences for foods overall and low-fat sweet foods remained after adjusting for differences in percentage body fat. In both fed and hungry states, active men had a greater implicit wanting for low-fat savory foods compared with inactive men, but only the differences in the fed state remained after adjusting for percentage body fat. Faster gastric emptying was found to be associated with greater liking for savory food and lower implicit wanting for high-fat food. Two studies in men and women differing in physical activity levels but matched for BMI (~23 kg/m²) found no differences in liking or wanting for high-fat relative to low-fat food in the hungry or fed states [34, 35].

In terms of correlational studies, objectively measured MVPA was found to be inversely associated with liking ($r = -0.25$, $p < 0.001$) and wanting ($r = -0.27$, $p = 0.001$) for high-fat relative to low-fat food measured by the LFPQ in 156 women across a range of BMI [41]. This is in line with a study showing that self-reported physical activity was associated with reduced fMRI responses to high-energy relative to low-energy food [39]. Another fMRI study in participants ranging in BMI found an inverse association between self-reported moderate-to-vigorous physical activity and brain response to food cues [40*]. This relationship appeared to be more prominent in the participants with obesity than the lean participants. In individuals with overweight/obesity and impaired fasting glucose and/or glucose tolerance, food compared with non-food brain activation was negatively associated with leisure-time physical activity [36•]. Interestingly, there was a positive association between brain activation and work-related physical activity, which lost statistical significance after adjusting for BMI and age, and there was no association with sport-related physical activity.

Overall, these studies suggest a reduction in food reward (both liking and wanting) with increasing levels of habitual physical activity, particularly at higher levels of adiposity. Those who accumulate more time in moderate-to-vigorous physical activity tend to prefer low-fat food and those who engage in more sedentary activity prefer high-fat food. These findings do not seem to be restricted to those who perform structured exercise. The inter-relationships between food reward, physical activity, and adiposity remain to be fully disentangled, as well as the mechanisms underlying these observed effects. One simple explanation could be that avoidance of high-fat food perceived to be unhealthy, preference for low-fat food and greater physical activity levels are all driven by a dispositional desire to be healthy and engage in a range of positive health behaviors [64, 65]. Alternatively, it has been proposed that physical activity may act as a reward “buffer” against liking and wanting for high-fat foods, whereas low levels of physical activity may render people more susceptible to hedonic eating [66, 67]. The possibility of stronger inverse associations between physical activity and food reward in lean groups versus groups with obesity suggests that exercise and leisure-time physical activity may be an effective strategy for controlling hedonic eating in people with obesity.

Acute Exercise Studies

At least eight studies have investigated the effect of acute exercise on food reward measured by the LFPQ which allows direct comparison of outcomes (Table 1). All these studies had a no-exercise control group except for Alkahtani et al. [42], but the exercise varied in intensity (low to high), modality (aerobic vs resistance; cycling vs swimming) or in muscle contraction type (eccentric vs concentric). Two studies
Table 1: Description of the observational, acute, and chronic training studies examining the impact of physical activity on food reward

| Reference | Participant characteristics | Exercise/physical activity details | Food reward method | Food reward results | Associations with appetite outcomes |
|-----------|----------------------------|------------------------------------|--------------------|---------------------|-------------------------------------|
| Beaulieu et al. 2017 [34] UK | BMI status < 29.9 kg/m² | PA level assessment: IPAQ and PA monitor (SenseWear) Active: ≥4 exercise sessions/week (MVPA = 182 (67) min/day) Inactive: ≤1 exercise session/week (MVPA = 103 (37) min/day) Exercise session: ≥40 min MVPA | - LFPQ: liking and implicit wanting bias for fat | - No difference in food reward (liking and wanting) between groups. | - Food intake: energy intake greater in high-fat relative to high-carbohydrate in both groups. |
| | Active: n = 20 (50% males) | | Setting: laboratory State: pre and post high-fat or high-carbohydrate lunch (ad libitum) | - Difference between liking/wanting: none | - Eating behavior traits: tendency for restraint to be higher in HiPA compared with LoPA |
| | Age: 30 (10) years BMI: 22.6 (1.9) kg/m² Inactive: n = 19 (42% males) | | | | - Body composition: HiPA had lower body fat percentage than LoPA |
| | Age: 30 (9) years BMI: 23.1 (2.7) kg/m² | | | | - Food intake: greater reduction in liking and wanting after HE preload relative to LE preload in all groups. |
| Beaulieu et al. 2017 [35] UK | BMI status < 29.9 kg/m² | PA level assessment: Tertiles of daily MVPA measured by PA monitor (SenseWear) HiMVPA: 174 (39) min/day ModMVPA: 121 (15) min/day LoMVPA: 83 (16) min/day | - LFPQ: liking and implicit wanting bias for fat | - No difference in food reward (liking and wanting) between groups. | - Eiting behavior traits: no differences between groups |
| | Active: n = 12 (33% males) | | Setting: laboratory State: pre and post preloads—HE (~ 700 kcal) and LE (~ 260 kcal) relative to water control (0 kcal) | - Difference between liking/wanting: none | - Body composition: no differences between groups |
| | Age: 29 (10) years BMI: 22.4 (2.1) kg/m² ModMVPA: n = 11 (27% males) | | | | - Body composition: no differences between groups |
| | Age: 26 (3) years BMI: 22.7 (2.2) kg/m² LoMVPA: n = 11 (27% males) | | | | - Eating behavior traits: no differences between groups |
| | Age: 30 (11) years BMI: 23.1 (2.9) kg/m² | | | | - Food intake: NR |
| Drummen et al. 2019 Netherlands [36•] | BMI status > 25 kg/m² | PA level assessment: Baecke questionnaire (work, sport, and leisure-time physical activity) Work = 2.6 (0.8) range 1.3–4.3 Sport = 2.6 (0.7) range 1.0–4.0 Leisure = 2.9 (0.7) range 1.5–4.4 Scores ranging from 1 (low level of PA) and 5 (high level of PA) | - fMRI: BOLD signals to high-energy food, low-energy food and non-food images | - Inverse association between leisure-time PA and food compared with non-food brain activation in the right thalamus, left middle cingulate gyrus, right precuneus, left putamen, and left angular gyrus. | - Eating behavior traits: positive association between brain activation and disinhibition. No association with restraint or susceptibility to hunger. |
| | n = 39 (56% males) | | Setting: laboratory State: after overnight fast | - Positive association between work-related physical activity and brain activation (disappeared after adjusting for BMI and age) | - Body composition: no association |
| | Age: 53 (11) years BMI: 32.3 (3.7) kg/m² Participants had impaired fasting glucose and/or glucose tolerance | | | | - No association with sport-related physical activity. |
| Horner et al. 2016 [38] Australia | BMI status 18–40 kg/m² | PA level assessment: Self-report and PA monitor (ActiGraph) Active: ≥4 exercise sessions/week (PA = 709 (239) kcal/day) Inactive: ≤1 exercise session/week (PA = 525 (185) kcal/day) Exercise session: ≥40 min MVPA | - LFPQ: liking and implicit wanting for HFSSW, LFSW, HPSA, LFSA | - No difference in food reward (liking and wanting) between groups. | - Gastric emptying: Inverse association with post-prandial changes in liking high-fat savory foods. Positive association with liking taste bias in hungry state (i.e., faster gastric emptying associated with greater liking for savory foods). No association with liking fat bias nor implicit wanting taste bias. Positive association with implicit wanting fat |
| Reference | Participant characteristics | Exercise/physical activity details | Food reward method | Food reward results | Associations with appetite outcomes |
|-----------|-----------------------------|-----------------------------------|-------------------|-------------------|------------------------------------|
| Killgore et al. 2013 [39] USA | Sex: females and males BMI status: 19.8–34.8 kg/m² n = 37 (59% males) Age: 30 (8) years BMI: 24.5 (3.7) kg/m² | PA level assessment: Self-reported habitual PA in min/week (typical days/week × duration/day) PA = 151 (160) min/week (range 0–540) | fMRI: response to high-energy food, low-energy food and non-food images Subjective food preferences: desire to eat depicted food item at that moment (VAS) | - Fed to hungry: Active had greater increase in liking for all food categories combined than inactive. - Difference between liking/wanting: Faster gastric emptying associated with liking for savory foods and slower gastric emptying associated with greater implicit wanting for high-fat foods. - Inverse association between habitual PA and fMRI responses (medial orbitofrontal cortex and left insula) to high-energy foods relative to low-energy foods - Inverse association between habitual PA and preference for high-energy savory foods - Inverse association between MVPA and brain response to food cues in middle insula and left postcentral gyrus. | - Subjective food preference: fMRI responses positively associated with preference for high-energy savory foods (not for high-energy sweet foods). No association between fMRI responses to high-energy relative to low-energy foods and preference for low-energy foods. - Food intake: NR - Eating behavior traits: NR - Body composition: NR |
| Luo et al. 2018 [40] USA | Sex: females and males BMI status: NR n = 40 (48% males) Lean individuals: n = 22 (46% males) Age: 21 (2) years BMI: 22.6 (1.9) kg/m² Individuals with obesity: n = 18 (50% males) Age: 22 (2) years BMI: 35.2 (4.0) kg/m² | PA level assessment: Self-reported from 3 to 5 24-h recalls over 2 months (mean daily minutes of MVPA i.e., activities ≥ 3 METs) Lean individuals: MVPA = 125 (84) min/day Individuals with obesity: MVPA = 134 (114) min/day | fMRI: responses to high-energy food and non-food images Subjecting: laboratory State: 9–11 am after overnight fast, task performed 20–30 min after 75 g glucose ingestion | - Inverse association between MVPA and brain response to food cues in middle insula and left postcentral gyrus. - Individuals with obesity: inverse association between MVPA and brain responses. - Lean individuals: non-significant inverse association between MVPA and brain responses. - Association between MVPA and brain responses stronger in males than females. | - Food intake: NR - Eating behavior traits: No association between PA and food cravings. Craving for sweet food (Control of Eating Questionnaire; CoEQ) positively associated with explicit liking and implicit wanting for sweet foods on the LFPQ. Craving for savory foods (CoEQ) associated with LFPQ explicit wanting for savory foods. Craving control (CoEQ) negatively associated with implicit wanting for high-fat foods. - Body composition: Fat mass index (FMI) but not waist circumference (WC) was inversely associated with explicit liking and implicit wanting for high-fat foods. |
| Oustric et al. 2018 [41] UK | Sex: females BMI status: 18.5–45.0 kg/m² n = 156 Age: 53 (11) years BMI: 32.3 (3.7) kg/m² Pooled data from 6 studies | PA level assessment: Quintiles of daily MVPA measured by PA monitor (SenseWear) Q1: 25 (8) min/day Q2: 53 (9) min/day Q3: 83 (9) min/day Q4: 120 (12) min/day Q5: 197 (62) min/day | LFPQ: liking and implicit wanting bias for fat/taste Setting: laboratory State: hungry (3–10 h fast) | - MVPA inversely associated with liking and implicit wanting fat bias. - MVPA positively associated with liking taste bias. - Q5 greater liking and wanting for low-fat foods, while Q1-Q3 greater liking and wanting for high-fat foods. - Difference between liking/wanting: none | - Food intake: NR - Eating behavior traits: No association between PA and food cravings. - Body composition: Fat mass index (FMI) but not waist circumference (WC) was inversely associated with explicit liking and implicit wanting for high-fat foods. |
| Reference | Participant characteristics | Exercise/physical activity details | Food reward method | Food reward results | Associations with appetite outcomes |
|-----------|-----------------------------|-----------------------------------|--------------------|---------------------|-------------------------------------|
| **Acute exercise studies** | | | | | sweet relative to savory foods. WC was positively associated with all liking and implicit wanting for high-fat relative to low-fat foods. FMI was also associated with implicit wanting for high-fat foods. |
| Alkahtani et al. 2014 [42] | Sex: males<br>BMI status: > 25 kg/m²<br>PA level: sedentary (criteria NR)<br><br>Australia<br><br>n = 12<br>Age: 29 (4) years<br>BMI: 29.1 (2.4) kg/m² | - Intensity: moderate-intensity interval training (MIIT; alternating between ± 20% FATₘₐₓ) vs. high-intensity interval training (HIIT; 85% VO₂ₘₐₓ)<br>- Type: cycle ergometer<br>- Duration: MIIT 5-min stages at ±20% FATₘₐₓ for 30 min, HIIT 15-s intervals and 15-s recovery (work load matched to MIIT; ~18 min)<br>- Timing: morning<br>- Control condition: no; MIIT vs. HIIT | - LFPO: liking and implicit wanting for HFSW, LFSW, HFSA, LFSA<br>- Setting: laboratory<br>- State: before and after exercise (after an overnight fast) | - Decrease in wanting and increase in liking for all the food categories independent of the intensity<br>- Difference between liking/wanting: liking increased while wanting decreased but without a control this response might be due to the effect of time rather than exercise | - Food intake: NR<br>- Eating behavior traits: NR<br>- Body composition: NR |
| Alkahtani et al. 2019 [43] | Sex: males<br>BMI status: NR<br>PA level: moderately active (2–5 h structured aerobic exercise/week)<br><br>Saudi Arabia<br><br>n = 14 (8 for food reward data)<br>Age: 24 (6) years<br>BMI: 23.4 (3.3) kg/m² | - Intensity: moderate (60% VO₂ₘₐₓ) interspersed with low (30% VO₂ₘₐₓ)<br>- Type: contraction type eccentric (downhill running at −12% inclination) vs. concentric (flat running)<br>- Duration: 5 stages of 8 min at 60%VO₂ₘₐₓ/2 min at 30%VO₂ₘₐₓ<br>- Timing: morning<br>- Control condition: yes; MIIT vs. HIIT | - LFPO: liking and implicit wanting bias for fat/taste<br>- Setting: laboratory<br>- State: before, after exercise and 24 h after exercise (before an ad libitum lunch) | - No change in food reward after exercise<br>- Difference between liking/wanting: greater liking of savory foods over sweet foods in downhill running than front running | - Food intake: no change<br>- Eating behavior traits: NR<br>- Body composition: NR |
| Crabtree et al. 2014 [44] | Sex: males<br>BMI status: 21.8–26.6 kg/m²<br>PA level: moderately active (2 h/week)<br><br>UK<br><br>n = 16<br>Age: 23 (3) years<br>BMI: 24.2 (2.4) kg/m² | - Intensity: high (70% VO₂ₘₐₓ)<br>- Type: treadmill run<br>- Duration: 60 min<br>- Timing: morning<br>- Control condition: yes; no exercise | - fMRI: BOLD signals to high- and low-energy food cues compared with non-food pictures<br>- Setting: laboratory<br>- State: fasted | - Decreased activation in the pallidum for high-energy food and increase for low-energy food after exercise<br>- Difference between liking/wanting: NR | - Food intake: NR<br>- Eating behavior traits: NR<br>- Body composition: NR |
| Evero et al. 2012 [45] | Sex: females and males<br>BMI status: < 25 kg/m²<br>PA level: habitually active (≥ 3 h/week)<br><br>USA<br><br>n = 30 (57% males) | - Intensity: high (83% HRₘₐₓ)<br>- Type: cycle ergometer<br>- Duration: 60 min<br>- Timing: morning<br>- Control condition: yes; no exercise | - fMRI: BOLD signals to high- and low-energy food cues compared with neutral control<br>- Setting: laboratory | - Exercise reduced the neuronal response to food cues in brain regions related with food reward (i.e., insula, putamen, rolandic operculum) | - Food intake: NR<br>- Eating behavior traits: NR<br>- Body composition: NR |
| Reference | Participant characteristics | Exercise/physical activity details | Food reward method | Food reward results | Associations with appetite outcomes |
|-----------|----------------------------|-----------------------------------|-------------------|---------------------|----------------------------------|
| Farah et al. 2012 [46] UK | Sex: females and males BMI status: no limits PA level: NR n = 27 (52% males) Female: n = 13 Age: 26 (3) years BMI: 22.8 (3.1) kg/m² Male: n = 14 Age: 36 (10) years BMI: 26.1 (3.3) kg/m² | - Intensity: moderate (6 METs) - Type: treadmill walk - Duration: 60 min - Timing: morning - Control condition: yes; no exercise | - State: fMRI was performed after exercise after an 8–12 h overnight fast | - Difference between liking/wanting: decrease in regions related to liking and wanting but no behavioral measures | - Food intake: NR - Eating behavior traits: NR - Body composition: NR |
| Finlayson et al. 2009 [47] UK | Sex: females BMI status: < 25 kg/m² PA level: 2.4 (1.2) engagements/week n = 24 Age: 24 (6) years BMI: 22.3 (2.9) kg/m² | - Intensity: moderate (6 METs) - Type: treadmill walk - Duration: 60 min - Timing: morning - Control condition: yes; no exercise | - VAS: liking - Setting: laboratory - State: immediately, 60, 120, and 180 min after exercise (overnight fasted) | - No change in liking - Difference between liking/wanting: wanting not measured | - Food intake: NR - Eating behavior traits: NR - Body composition: NR |
| Martins et al. 2015 [48] Norway | Sex: females and males BMI status: > 25 kg/m² PA level: sedentary (criteria NR) n = 12 (42% males) Age: 33 (10) years BMI: 32.3 (2.7) kg/m² | - Intensity: HIIT and ½ HIIT (all out; average ~ 85% HRmax) continuous cycling - Duration: HIIT (8-s intervals and 12-s recovery for 250 kcal; ~ 18 min), ½ HIIT (8-s intervals and 12-s recovery for 125 kcal; ~ 9 min), continuous exercise (250 kcal; ~ 27 min) - Timing: morning - Control condition: yes; no exercise | - LFPQ: relative preference (food choice), liking and implicit wanting bias for fat - Setting: laboratory - State: before and after exercise (2 h after a fixed breakfast, kcal NR) and after an ad libitum lunch 30-min post exercise | - Increase in implicit wanting after exercise in those who compensated or ate more at the ad libitum lunch in response to exercise - Changes in implicit wanting but not liking - Food intake: After exercise some individuals increased their energy intake (compensators) and had enhanced implicit wanting - Eating behavior traits: NR - Body composition: NR |
| McNeil et al. 2015 [49] Canada | Sex: females and males BMI status: < 25 kg/m² PA level: inactive (<150 min/week) n = 16 (50% males) Age: 22 (3) years BMI: 22.8 (1.8) kg/m² | - Intensity: high (aerobic 70% VO2peak, resistance 70% 1-repetition maximum) - Type: aerobic vs. resistance - Duration: aerobic ~ 24 min, resistance ~ 86 min (matched for energy expenditure at 4 kcal/kg; ~ 275 kcal) - Timing: morning - Control condition: yes; no exercise | - LFPQ: relative preference (food choice), liking and implicit wanting bias for fat/taste - Setting: laboratory - State: pre and post ad libitum lunch 30 min after exercise (standardized breakfast of 534 kcal consumed ~ 1.5 h before exercise) | - Decrease in the relative preference for high-fat relative to low-fat foods after both exercise - Food intake: no change - Eating behavior traits: NR - Body composition: no difference in bodyweight - Body composition: no difference in bodyweight | - Increase in implicit wanting after exercise in those who compensated or ate more at the ad libitum lunch in response to exercise - Changes in implicit wanting but not liking - Food intake: After exercise some individuals increased their energy intake (compensators) and had enhanced implicit wanting - Eating behavior traits: NR - Body composition: NR |
| Miguet et al. 2018 [50] Canada | Sex: females and males (adolescents) | - Intensity: high (70%, 75%, 80%, 85%, and 90% HRmax) - Type: aerobic vs. resistance - Duration: aerobic ~ 24 min, resistance ~ 86 min (matched for energy expenditure at 4 kcal/kg; ~ 275 kcal) - Timing: morning - Control condition: yes; no exercise | - LFPQ: relative preference (food choice), liking and implicit wanting bias for fat/taste - Setting: laboratory - State: before and after exercise (2 h after a fixed breakfast, kcal NR) and after an ad libitum lunch 30-min post exercise | - Decrease in the relative preference for high-fat relative to low-fat foods after both exercise - Food intake: no change at lunch and dinner | - Food intake: decrease in energy intake at lunch and dinner |
| Reference          | Participant characteristics | Exercise/physical activity details | Food reward method | Food reward results | Associations with appetite outcomes |
|-------------------|----------------------------|----------------------------------|-------------------|-------------------|-------------------------------------|
| **France**        | BMI status: > 29.9 kg/m²    | - Type: high-intensity interval  | - Setting: laboratory | - Decrease in implicit wanting for sweet | - Eating behavior traits: NR        |
|                   | PA level: inactive (<2 h/week) | training cycling                  | - State: pre and post ad libitum lunch | in the exercise condition vs. increase in | - Body composition: NR              |
| n = 33 (36% males)| Age: 13 (1) years BMI: 35.0 (4.3) kg/m² | - Duration: 5 × 2-min increasing | 30 min after exercise (standardized | - Difference between liking/wanting: | - Food intake: increase in ad libitum |
|                   |                           | intensity intervals followed by  | breakfast of 500 kcal consumed 2.5 h | implicit wanting but not liking is     | energy intake after swimming but not | energy intake after cycling          |
|                   |                           | 30-s recovery (15 min)           | before exercise)      | decreasing          | Eating behavior traits: NR          |
|                   |                           | - Timing: morning                | - Difference between liking/wanting: | - Body composition: NR               |
|                   |                           | - Control condition: yes; no exercise | no changes           | - Food intake: (self-reported) no change |
|                   |                           | - State: pre and post fixed lunch | - Individual variability in the BOLD | - Eating behavior traits: NR          |
|                   |                           | 30 min after exercise            | signals after exercise might be explained by changes in the brain opioid system. Participants who showed most increases in endogenous opioid release also had highest anticipatory fMRI reward responses following the exercise | - Body composition: NR               |
|                   |                           | - Control condition: yes; no exercise | - No effects of exercise vs rest on neuronal responses. | - Food intake: NR                     |
|                   |                           |                                  | - State: post-exercise fasted for 3 h before the scans | - Eating behavior traits: NR          |
|                   |                           |                                  | - Setting: laboratory | - Food intake: NR                     |
|                   |                           |                                  | - Difference between liking/wanting: | - Eating behavior traits: NR          |
|                   |                           |                                  | no differences       | - Body composition: NR               |
|                   |                           |                                  | - No change in food reward | - Fat intake: increase in | - Body composition: NR               |
|                   |                           |                                  | - Difference between liking/wanting: no | reward | - Body composition: NR               |
|                   |                           |                                  | differences         | - Food intake: (self-reported) no change |
|                   |                           |                                  | - Tendency for a main effect of trial for | - Eating behavior traits: NR          |
|                   |                           |                                  | implicit wanting fat bias (post hoc: | - Body composition: NR               |
|                   |                           |                                  | cycling < control, cycling < | - Food intake: (self-reported) no change |
|                   |                           |                                  | swimming)            | - Eating behavior traits: NR          |
|                   |                           |                                  | - No impact of swimming or cycling on | - Body composition: NR               |
|                   |                           |                                  | other food reward parameters. | - Food intake: (self-reported) no change |
|                   |                           |                                  | - Difference between liking/wanting: | - Eating behavior traits: NR          |
|                   |                           |                                  | Changes in implicit wanting but not | - Body composition: NR               |
|                   |                           |                                  | liking              | - Food intake: (self-reported) no change |
|                   |                           |                                  | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
|                   |                           |                                  | - No changes in wanting. | - Food intake: (self-reported) no change |
|                   |                           |                                  | - Difference between liking/wanting: not assessed | - Eating behavior traits: NR          |
| **Thackray et al.** | Sex: females and males BMI status: 18.5–29.9 kg/m² | - Type: swimming vs. cycling     | - LFPQ: relative preference (food choice), liking and implicit wanting bias for fat/taste | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
| unpublished       | PA level: habitually active | - Duration: 6 × 8-min intervals with 2-min recovery | - State: post-exercise (3 h after | - No changes in wanting. | - Eating behavior traits: NR          |
| n = 32            | Age: 23 (2) years BMI: 23.9 (2.6) kg/m² | - Timing: morning | 750 kcal for males, 525 kcal for females, and before ad libitum lunch meal | - Difference between liking/wanting: not assessed | - Eating behavior traits: NR          |
| **Thivel et al. 2019 [51]** | Sex: females and males BMI status: <25 kg/m² | - Type: moderate-to-high intensity (RPE of 15 “hard”) | - Setting: laboratory | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
| France            | PA level: moderately active | - Duration: low intensity 45 min, high intensity 30 min | - Tendency: laboratory | - Difference between liking/wanting: not assessed | - Eating behavior traits: NR          |
| (150–240 min/week)| Age: 21 (1) years BMI: 22.3 (2.9) kg/m² | - Timing: morning | - Different between liking/wanting: no differences | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
| n = 19 (52% males)|                           | - Control condition: yes; no exercise | - No changes in wanting. | - Difference between liking/wanting: not assessed | - Eating behavior traits: NR          |
| **Saanijoki et al. 2018 [52]** | Sex: males BMI status: 19.9–26.9 kg/m² | - Intensity: low 50% VO_{max}, high 75% VO_{max} | - LFPQ: relative preference, liking and implicit wanting bias for fat/taste | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
| Finland           | PA level: NR               | - Type: cycling                   | - State: post-exercise (3 h after 650 kcal for males, 525 kcal for females, and before ad libitum lunch meal) | - Difference between liking/wanting: not assessed | - Eating behavior traits: NR          |
| n = 24            | Age: 27 (5) years BMI: 23.5 (1.6) kg/m² | - Duration: 60 min | - Setting: laboratory | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
| **Chronic exercise training studies** |                                | - Timing: NR                      | - State: post-exercise fasted for 3 h before the scans | - Difference between liking/wanting: not assessed | - Eating behavior traits: NR          |
| Alkahtani et al. 2014 [53] | Sex: males BMI status ≥ 25 kg/m² | - Intensity: moderate (74% HR_{max}) | - Setting: laboratory | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
| Australia         | PA level: inactive (criteria NR) | - Type: aerobic cycling            | - State: post-exercise fasted for 3 h before the scans | - Difference between liking/wanting: not assessed | - Eating behavior traits: NR          |
| n = 10            | Age: 29 (4) years | - Frequency: 3 days/week for 4 week (cross-over with 6-week washout) | - Setting: laboratory | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
|                  | Moderate-intensity interval training (MIIT): BMI baseline = 30.7 (3.5) kg/m² | - Intensity: MIIT ± 20% workload at 45% VO_{peak}, HIIT 90% VO_{peak} | - State: post and pre 45-min cycling at 45% VO_{peak} | - Difference between liking/wanting: not assessed | - Eating behavior traits: NR          |
|                  | BMI post = 30.8 (3.5) kg/m² | - Type: MIIT vs. HIIT              | - Measurement time points: week 0 and week 4 in each intervention | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
|                  |                             | - Duration: 30–45 min (MIIT 5-min stages alternating between ±20%) | - Setting: laboratory | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
|                  |                             | - LFPQ: liking and implicit wanting for | - State: post and pre 45-min cycling at 45% VO_{peak} | - Difference between liking/wanting: not assessed | - Eating behavior traits: NR          |
|                  |                             | HFSW, LFSW, HFSA, LFSA | - Measurement time points: week 0 and week 4 in each intervention | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
|                  |                             | - Setting: laboratory | - State: post and pre 45-min cycling at 45% VO_{peak} | - Difference between liking/wanting: not assessed | - Eating behavior traits: NR          |
|                  |                             | - State: post and pre 45-min cycling at 45% VO_{peak} | - Measurement time points: week 0 and week 4 in each intervention | - Tendency for a decrease in implicit wanting for fat intake after MIIT and decrease with HIIT. | - Eating behavior traits: NR          |
| Reference                  | Participant characteristics | Exercise/physical activity details | Food reward method | Food reward results | Associations with appetite outcomes |
|---------------------------|----------------------------|-----------------------------------|--------------------|---------------------|--------------------------------------|
| Beaulieu et al. 2019 [54] | Sex: females and males     | BMI status: 26.0–38.0 kg/m²       | - Frequency: 5 days/week for 12 weeks | - Decrease in wanting after training | - Food intake: reduction in high fat ad libitum dinner intake but no change in daily high-fat energy intake [55] |
| UK                        | PA level: in active (≤ 2 h/week) | Exercisers: n = 46 (35%) males | - Intensity: 70% HR<sub>max</sub> | - No change in liking | - Eating behavior traits: decrease in disinhibition and binge eating score |
|                           | Age: 43 (8) years           | BMI baseline = 30.5 (3.8) kg/m²   | - Type: aerobic (treadmill, rower, cycle ergometer, and elliptical) | - Difference between liking/wanting: yes | - Body composition: reduction in body weight and percentage body fat, but not associated with changes in wanting |
|                           | BMI post = 29.9 (4.0) kg/m² | Controls: n = 15 (40%) males      | - Duration: 500 kcal (males 40–45 min, females ~60 min) | - changes in wanting but not liking | - Chronic exercise: reduction in neuronal responses observed in the bilateral parietal cortices, left insula and visual cortex. |
|                           | Age: 41 (11) years          | BMI baseline = 31.4 (3.7) kg/m²   | - Timing: NR       | - Food intake: self-reported energy intake lower after training compared with baseline but no change in macronutrient intake. No association with changes in neuronal responses. |
|                           | BMI post = 31.8 (3.9) kg/m² | - Supervision: yes                | - Control group: no | - Eating behavior traits: no change in dietary restraint or disinhibition | - Chronic + acute exercise: intermediate attenuation of the response to visual food cues in brain region important in food regulation compared with chronic exercise and baseline. |
| Comier et al. 2012 [56]  | Sex: females and males      | BMI status: > 25 kg/m²            | - Frequency: 5 days/week for 24 weeks | - Difference between liking/wanting: NR | - Body composition: reduction in body fat percentage. Changes in anterior insula responses positively associated with changes in body mass and fat mass. |
| USA                       | PA level: NR                | n = 12 (42% males)               | - Intensity: up to 75% VO<sub>max</sub> | - Chronic exercise: reduction in neuronal responses. | - Food intake: NR |
|                           | Age: 38 (10) years          | BMI baseline = 33.3 (4.3) kg/m²   | - Type: treadmill | - Eating behavior traits: NR | - Eating behavior traits: NR |
|                           | BMI post = NR               | BMI baseline = 33.3 (4.3) kg/m²   | - Duration: up to 500 kcal/day (40–60 min/day) | - Difference between liking/wanting: NR | - Body composition: greater fat mass loss in responders |
|                           | Age: 41 (10) years          | - Timing: NR                     | - Timing: NR       | - Increase in relative preference for high-fat sweet food in non-responders. | - Food intake: NR |
|                           | Non-Responders (compensators): n = 20 (43% males) | | - Supervision: yes | - Increase in relative preference for high-fat sweet food in non-responders. | - Eating behavior traits: NR |
|                           | Age: 41 (9) years           | BMI baseline = 32.3 (4.3) kg/m²   | - Control group: no | - Increase in relative preference for high-fat sweet food in non-responders. | - Body composition: greater fat mass loss in responders |
|                           | BMI post = 30.9 (4.3) kg/m² | Non-Responders (compensators): n = 14 (50% males) | | | |
|                           | Age: 37 (12) years          | BMI baseline = 29.7 (2.2) kg/m²   | | | |
|                           | BMI post = 29.3 (2.5) kg/m² | | | | |
| Finlayson et al. 2011 [57]| Sex: females and males      | BMI status: 26.0–38.0 kg/m²       | - Frequency: 5 days/week for 12 weeks | - Increase in liking after exercise in non-responders compared with responders at baseline and week 12. | - Food intake: NR |
| UK                        | PA level: in active (≤ 2 h/week) | Responders (non-compensators): n = 20 (43% males) | - Intensity: 70% HR<sub>max</sub> | - Increase in explicit wanting for high-fat sweet foods in non-responders. | - Eating behavior traits: NR |
|                           | Age: 41 (9) years           | BMI baseline = 32.3 (4.3) kg/m²   | - Type: aerobic (treadmill, rower, cycle ergometer, and elliptical) | - Increase in relative preference for high-fat sweet food in non-responders. | - Body composition: greater fat mass loss in responders |
|                           | BMI post = 30.9 (4.3) kg/m² | Non-Responders (compensators): n = 14 (50% males) | - Duration: 500 kcal (males 40–45 min, females ~60 min) | - Difference between liking/wanting: implicit wanting NR | |
|                           | Age: 37 (12) years          | BMI baseline = 29.7 (2.2) kg/m²   | - Timing: NR       | - Difference between liking/wanting: implicit wanting NR | |
|                           | BMI post = 29.3 (2.5) kg/m² | Non-compensators: n = 15 (33% males) | | | |
| Finlayson et al. unpublished | Sex: females and males      | BMI status: 26.0–38.0 kg/m²       | - Frequency: 5 days/week for 12 weeks | - Decrease in wanting after training | - Food intake: tendency for non-compensators to decrease ad libitum dinner meal size from baseline to post-intervention that was not seen in compensators. |
| UK                        | PA level: inactive (≤ 2 h/week) | BMI baseline = 33.3 (4.3) kg/m²   | - Intensity: 70% HR<sub>max</sub> | - No change in liking | - Food intake: NR |
|                           | Non-compensators: n = 15 (33% males) | BMI post = 30.9 (4.3) kg/m² | - Type: aerobic (treadmill, rower, cycle ergometer, and elliptical) | - No change in wanting | - Eating behavior traits: NR |

Table 1 (continued)
| Reference | Participant characteristics | Exercise/physical activity details | Food reward method | Food reward results | Associations with appetite outcomes |
|-----------|-----------------------------|-----------------------------------|------------------|-------------------|-----------------------------------|
| Martin et al. 2019 [58] USA | Age: 42 (8) years BMI baseline = 30.7 (4.9) kg/m² BMI post = 29.1 (5.0) kg/m² Compensators: n = 15 (33% males) | Duration: 500 kcal (males 40–45 min, females ~ 60 min) Timing: NR Supervision: yes Control group: yes, no exercise | Measurement time points: week 0 and week 12 | Food whereas non-compensators showed no difference between high-fat and low-fat food. Greater baseline reward for high-fat food in compensators reduced following the exercise intervention. In the non-compensators, small increase in liking for high-fat food after exercise training, but a simultaneous decrease in wanting for high-fat food. Difference between liking/wanting: yes, non-compensators increased liking but decreased wanting for high-fat food post-intervention. | Eating behavior traits: NR Body composition: significant reduction in BMI, body mass, fat mass and WC in non-compensators, whereas no changes in compensators, and increase in body mass and WC. |
| Martins et al. 2017 [60] Norway | Age: 48 (11) years BMI baseline = 31.4 (4.6) kg/m² BMI post = NR (~ 31.3 kg/m²) 20 KKW: n = 51 (29% males) | Frequency: 3–5 days/week (self-selected) for 24 weeks Intensity: 65–85% VO₂peak (self-selected) Type: treadmill Duration: 8 KKW ~ 55 min/session (~ 1760 kcal/week) Timing: NR Supervision: yes Control group: yes, no exercise | Food Preference Questionnaire [59] preferences for food classified as alongside 2 components: fat (2 factors: High Fat and Low Fat) and carbohydrate (3 factors: High Simple Sugar, High Complex CHO, and Low CHO/High Protein) Setting: laboratory State: NR Measurement time points: week 0 and week 24 | No effect of exercise on liking or wanting Difference between liking/wanting: no change | Eating behavior traits: NR Body composition: difference in body mass and body fat percentage loss between 20 KKW and control. |
| Reference | Participant characteristics | Exercise/physical activity details | Food reward method | Food reward results | Associations with appetite outcomes |
|-----------|-----------------------------|-----------------------------------|--------------------|---------------------|--------------------------------------|
| Miguet et al. 2019 [62] | Sex: females (premenopausal) | BMI status > 27 kg/m² | - Frequency: 5 days/week for 12–14 weeks | LFPQ: liking and implicit wanting bias for fat/taste | Decrease in wanting for fat | Food intake: no change in lunch EI at 10 months |
| | PA level: inactive (<150 min/week) | Low intensity: n = 11 week. Moderate intensity: n = 10 | - Intensity: LOW (40% VO₂reserve) vs. moderate (MOD; 60% VO₂reserve) | Setting: laboratory | Eating behavior traits: increase in uncontrolled eating and emotional eating at 5 and 10 months |
| | Age: 31 (11) years | BMI baseline = 35.1 (6.2) kg/m² | - Type: aerobic (treadmill or cycle ergometer) | State: post breakfast/pre exercise (ad libitum) | Body composition: decrease in percentage fat mass at 5 and 10 months |
| | | BMI post = NR (~ 35.5 kg/m²) | - Duration: 30 min to 60 min | Measurement time points: baseline, 5 months, 10 months | |
| | Thivel et al. 2019 [63] | Sex: females and males (adolescents) | BMI status > 90th percentile for sex and age | LFPQ: relative preference (food choice), liking and implicit wanting bias for fat/sweet | - Eccentric group: increase in preference for high-fat foods and savory foods (decrease in sweet bias). Increase in implicit wanting for savory foods (decrease in sweet bias). |
| | PA level: concentric | Eccentric: n = 12 (50% males) | BMI baseline = 34.8 (5.5) kg/m² | Setting: laboratory | - Group by time interaction showed concentric group increased preference and implicit wanting for sweet foods while eccentric decreased. |
| | | Age: 14 (1) years | BMI post = 29.0 (4.5) kg/m² | State: fasted | - Food intake: total daily energy intake increased in both groups from baseline to week 24, but only increased in concentric group from week 12 to 24. |
| | | Concentric: n = 12 (50% males) | - Duration: 30 min to 45 min | Measurement time points: baseline, week 12 and week 24 | - Eating behavior traits: NR |

**Note:** All texts are translated from French to English. The table includes details about participant characteristics, exercise and physical activity, food reward methods, food reward results, and associations with appetite outcomes.
showed a decrease in food reward after acute exercise compared with the sedentary control. McNeil and colleagues revealed a decrease in the preference for high-fat relative to low-fat food independently of the modality of exercise (aerobic or resistance) in inactive adults within the normal range of BMI [49]. Miguet and colleagues showed a decrease in implicit wanting for sweet relative to savory food in response to an ad libitum meal after a session of high intensity interval exercise in inactive adolescents with obesity [50]. Interestingly, no change in food intake was observed in the McNeil study whereas a decrease in total energy intake (both lunch and dinner) was noted in the Miguet study. This might be related to the fact that changes in implicit wanting are a greater driver of food intake than changes in liking. Also, the McNeil study might have been underpowered to detect a change in implicit wanting. Four studies showed no changes in food reward (fat or taste bias for liking, relative preference or implicit wanting).

One study compared eccentric vs concentric exercise on moderately active men (BMI 23.4 ± 3.3 kg/m^2) and showed no effect on either appetite sensations, appetite-related hormones, or food reward [43]. Three studies compared the intensity of exercise (low versus high [51] or high- or moderate-intensity intermittent cycling [42, 48]). Two reported no effects on food reward or food intake [48, 51] whereas one found a decrease in wanting and increase in liking after both high- and moderate-intensity exercise [42]. Of note, these studies were conducted in moderately active normal-weight adults [51] and inactive adults with overweight/obesity [42, 48]. A recently completed study compared bouts of swimming or cycling to a no-exercise control in a within-subjects design (Thackeray et al. unpublished). While they found that energy intake was increased after swimming but not cycling compared with control, no differences in food reward were detected except for a tendency for a main effect of trial for implicit wanting fat bias with wanting being smaller after cycling relative to swimming and control. Lastly, Finlayson and colleagues demonstrated that implicit wanting was increased in response to moderate-intensity exercise only in those individuals that increased their energy intake relative to no exercise (i.e., compensators) [47]. Consequently, even with the same methodology to assess food reward, the response to acute exercise seems to be equivocal and subject to individual variability. This could be explained by methodological issues; even though the same tool is used, the studies were conducted in different countries (UK, Saudi Arabia, Canada, France, and Norway) and the food images used may not have been cross-culturally validated [68]. The sample sizes were relatively small for most of the studies (ranging from 12 to 33), including mainly both genders and with different ranges of BMI. However, it can be noticed that exercise seems to affect food reward more clearly in inactive individuals compared with active ones in both adolescents and adults. One tentative hypothesis could be that inactive individuals (within the non-regulated zone of the J-shape curve)
would benefit more from acute exercise than active individuals for whom the appetite control system is more sensitive.

Farah and colleagues used a computer-based task to measure the effect of acute exercise on liking (visual analogue scale) and other non-homeostatic indicators (ideal portion size, food utility, hunger) [46]. They found that a 60-min moderate-intensity exercise bout reduced hunger and ideal portion size but not liking. This is in concordance with previous results showing that implicit wanting rather than liking might be influenced by exercise. However, the physical activity level of the participants was not reported, and implicit wanting was not measured.

Acute exercise has also been shown to have an effect on brain reward measured by BOLD response to food cues with fMRI. Evero and colleagues showed that a 60-min high-intensity exercise bout decreased the neuronal response to food cues in brain regions related to food reward, visual attention, and inhibitory control [45]. Interestingly, regions related to both liking (i.e.,
insula, orbitofrontal cortex) and wanting (i.e., putamen) were reduced after exercise. This is in line with another study that found that exercise increases neural responses in reward-related regions in response to images of low-calorie foods and suppresses activation during the viewing of high-calorie foods [44]. These central responses were associated with exercise-induced changes in peripheral signals related to appetite control and hydration status. However, liking and implicit wanting were not measured directly in these studies (i.e., behavioral measures) nor was food intake. Lastly, Saanikoji et al. found no effect of an acute moderate-intensity aerobic exercise on brain food reward in lean men [52]. However, they showed that individuals who increased the most in endogenous opioid release had the highest brain reward response after the exercise compared with the control. Consequently, the opioid system might contribute to explain some individual variability in the food reward responses to exercise.

**Chronic Exercise Training Studies**

As mentioned above, our recent systematic review on weight management interventions found limited evidence on the impact of exercise interventions on food reward [6••]. Among the included studies, two investigated the impact of high-intensity interval exercise compared with either moderate-intensity interval training [53] or continuous training [60]. Using a cross-over design, Alkahtani et al. [53] found that in response to acute exercise after a 4-week exercise intervention, liking for high-fat savory food seemed to increase after MIIT and decrease after HIIT in men with overweight or obesity (interaction p = 0.09). Another study in individuals with obesity found no changes in food reward in response to a breakfast meal (hungry and fed states) after a 12-week intervention of either high-intensity interval exercise (125 or 250 kcal, 3 days/week) or moderate-intensity continuous exercise (250 kcal, 3 days/week) [60]. In another study, no changes in liking or implicit wanting for high-fat relative to low-fat food in the hungry state were observed after a 12-week aerobic exercise intervention (500 kcal, 5 days/week), although a trend towards a reduction in wanting was noted [69]. However, more recent analyses with a non-exercising control group revealed that in response to a high-fat and high-carbohydrate fixed lunch (hungry and fed states), overall implicit wanting decreased after the 12-week exercise intervention, whereas no changes in explicit liking were found [54]. This is corroborated by another study that found a decrease in implicit wanting for high-fat relative to low-fat food in women who underwent a 3-month exercise intervention (300 kcal, 5 days/week) [62]. When food reward was measured in response to an exercise bout post-intervention in that study, there was also a decrease in liking for savory foods whereas liking for savory foods increase after acute exercise at baseline. Thus, it appears that chronic exercise training may modulate the food reward response to acute exercise in inactive individuals, also shown in an fMRI study [56].

Interestingly, changes in food reward in the study by Beaulieu et al. [54] were not associated with changes in body weight or composition, suggesting a potential independent effect of exercise. Indeed, an inverse association was found between changes in leptin (adjusted for percentage body fat) and changes in liking, but not wanting, for high-fat food [69]. Thus, leptin may have a role in mediating changes in food reward during exercise training in individuals with overweight/obesity. In contrast, a 6-month exercise intervention led to a reduction in the fasted neuronal response to food compared with non-food, and some of these changes were associated with changes in fat mass, body weight and leptin [56]. These findings are interesting in light of the seminal study by Rosenbaum [70], who reported that leptin replacement after >10% weight loss using a liquid formula diet, modulated food cue-elicited neuronal activation in reward-related regions (consistent with wanting), but did not affect liking for the diet. Beyond leptin, it is known that weight loss also impacts fasting levels of ghrelin. For example, the RESOLVE study (NCT00917917) showed that long-term physical activity may reverse the early enhancing effect of body weight loss on plasma ghrelin [71]. Future studies should examine whether favorable effects of exercise-induced weight loss on food reward can be partly explained by modulation of ghrelin as well as leptin.

Differences in food preferences have also been found between individuals who compensated (less than expected weight loss based on median split) compared with non-compensators during a 6-month intervention expending either ~700 kcal/week or ~1760 kcal/week [58]. Compensators had reduced preference for low-fat and high-carbohydrate food relative to non-compensators. Indeed, the hedonic response to acute exercise also appears to impact weight loss outcomes during chronic exercise training [57]. We have shown that after acute exercise, liking for all foods and wanting for high-fat sweet food increased only in compensators to a 12-week exercise intervention (those who achieved less than expected weight loss), compared with no change in non-compensators (those achieving at or above expected weight loss). These differences were independent of the exercise intervention and weight loss [57] and add to other evidence of improved appetite control in this group [72]. In a further unpublished study from our laboratory where sub-groups of 12-week exercise intervention non-compensators and compensators were compared with a non-exercising control group (Fig. 1), we observed that prior to the exercise intervention, compensators showed a strong liking and wanting for high-fat food whereas non-compensators showed no difference between high-fat and low-fat food. Secondly, we found that the greater reward for high-fat food in compensators reduced following the exercise intervention, compared with no change in controls. Lastly, there appeared to be a unique pattern of
change in liking and wanting in the non-compensators who showed a small increase in liking for high-fat food after exercise training, but a simultaneous decrease in wanting for high-fat food.

In adolescents with obesity, eccentric cycling exercise as part of a 12-week inpatient multidisciplinary weight loss intervention increased the relative preference for high-fat food and increased both the relative preference and implicit wanting for savory food, whereas no changes were observed in response to concentric exercise training [63]. Another study in adolescents with obesity showed that during a 10-month inpatient multidisciplinary weight loss intervention including physical activity, liking for food in the hungry state increased from baseline to 5 months, then returned to baseline values at 10 months, whereas liking for food in the fed state decreased (Miguet et al., under review). There were no changes in wanting observed.

These studies are suggestive that chronic exercise improves food reward (reduced response to high-energy foods and increased response to low-energy foods). However, the effect sizes were relatively small and inter-individual variability tended to be large. Two studies found a reduction in implicit wanting for high-fat relative to low-fat foods after exercise training [54, 62]. This may be a result of a direct effect of exercise on brain regions related to food reward, as shown by the fMRI studies included in the current review, and others [73, 74]. Furthermore, as exercise affects cognition and executive function, it has been proposed that processes such as inhibitory control could have a moderating effect on wanting and modulate eating behavior [66].

Another two studies found an increase in liking after exercise training, which might be explained by concomitant improvements in homeostatic appetite control in these studies (a small increase in hunger or a reduction in fasting leptin concentrations). Individual differences in food reward appear to act as pre-existing moderators of the impact of exercise training on weight loss and suggest that those with healthier preferences or better satiety signaling at baseline appear to lose more weight with exercise. No clear evidence exists regarding the optimal mode, frequency, intensity, duration, and time of day for exercise to have the most impact on food reward. Further systematic research into these factors is warranted.

**Conclusions**

One of the perceived barriers for engaging in exercise is its potential to promote hedonic eating. Food reward plays an important role in weight management through its intervening status between the nutrient requirements of the body and hedonic inputs from the food environment that promote food intake. This review brings together current evidence from observational, acute, and chronic exercise training studies to inform public debate on the impact of physical activity on food reward. A conceptual model, building on previous theory [19••] is shown in Fig. 2. Observational studies show that performance of moderate-to-vigorous physical activity is associated with lower liking and wanting for high-fat or high-energy food, and higher liking for low-fat/low-energy food. These findings may reflect improved appetite control and are supported by evidence from chronic exercise training interventions. Where exercise training leads to successful weight loss, it appears to be accompanied by a dissociation between liking and wanting evidenced by a reduction in wanting for high-energy food but increase in liking for low-energy food. Acute bouts of exercise tend to only impact behavioral indices of food reward in less active individuals or those with poor appetite control, where it tends to result in reduced food reward. These findings are corroborated by observational studies that demonstrate greater liking and especially wanting for high-energy foods (and greater susceptibility to food cravings) in inactive individuals. Food reward does not counteract the benefit of physical activity for obesity management. Rather, exercise appears to accompany positive changes in food preferences in line with improvements in appetite control.

**Compliance with Ethical Standards**

**Conflict of Interest** The authors declare no conflict of interest.

**Human and Animal Rights and Informed Consent** This article does not contain any studies with human or animal subjects performed by any of the authors.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

**References**

Papers of particular interest, published recently, have been highlighted as:

- Of importance
- Of major importance

1. Guess N. A qualitative investigation of attitudes towards aerobic and resistance exercise amongst overweight and obese individuals. BMC Res Notes. 2012;5:191–12. https://doi.org/10.1186/1756-0500-5-191.
2. Leone LA, Ward DS. A mixed methods comparison of perceived benefits and barriers to exercise between obese and nonobese women. J Phys Act Health. 2013;10(4):461–9.
the impact of habitual physical activity on the mechanisms of appetite control that proposes an updated model of the J-shape relationship between physical activity level and energy intake, with body composition, satiety signaling and non-homeostatic factors playing a role.

Berthoud HR, Munzberg H, Morrison CD. Blaming the brain for obesity: integration of hedonic and homeostatic mechanisms. Gastroenterology. 2017;152(7):1728–38. https://doi.org/10.1053/j.gastro.2016.12.050.

Pool E, Semnwald V, Delplanque S, Brosch T, Sander D. Measuring wanting and liking from animals to humans: a systematic review. Neurosci Biobehav Rev. 2016;63:124–42. https://doi.org/10.1016/j.neubiorev.2016.01.006.

Berridge KC, Robinson TE, Aldridge JW. Dissecting components of reward: ‘liking’, ‘wanting’, and learning. Curr Opin Pharmacol. 2009;9(1):65–73. https://doi.org/10.1016/j.coph.2008.12.014.

Dalton M, Finlayson G. Psychobiological examination of liking and wanting for fat and sweet taste in trait binge eating females. Physiol Behav. 2014;136:128–34. https://doi.org/10.1016/j.physbeh.2014.03.019.

French SA, Mitchell NR, Wolfson J, Finlayson G, Blundell JE, Jeffery RW. Questionnaire and laboratory measures of eating behavior. Associations with energy intake and BMI in a community sample of working adults. Appetite. 2014;72:50–8. https://doi.org/10.1016/j.appet.2013.09.020.

de Castro JM, Bellisle F, Dalix AM, Pearcy SM. Palatability and intake relationships in free-living humans. Characterization and independence of influence in North Americans. Physiol Behav. 2000;70(3–4):343–50. https://doi.org/10.1016/s0031-9384(00)00264-x.

Cox DN, Perry L, Moore PB, Vallis L, Mela DJ. Sensory and hedonic associations with macronutrient and energy intakes of lean and obese consumers. Int J Obes Relat Metab Disord. 1999;23(4):403–10. https://doi.org/10.1038/sj.ijo.0800836.

de Araujo IE, Schatzker M, Small DM. Rethinking food reward. Annu Rev Psychol. 2019. https://doi.org/10.1146/annurev-psych-122216-011643.

Mela DJ. Eating for pleasure or just wanting to eat? Reconsidering sensory hedonic responses as a driver of obesity. Appetite. 2006;47(1):10–7. https://doi.org/10.1016/j.appet.2006.02.006.

Finlayson G, King N, Blundell J. The role of implicit wanting in relation to explicit liking and wanting for food: implications for appetite control. Appetite. 2008;50(1):120–7. https://doi.org/10.1016/j.appet.2007.06.007.

Dalton M, Finlayson G, Hill A, Blundell J. Preliminary validation and principal components analysis of the Control of Eating Questionnaire (CoEQ) for the experience of food craving. Eur J Clin Nutr. 2015;69(12):1313–7. https://doi.org/10.1038/ejcn.2015.57.

Hill AJ, Weaver CF, Blundell JE. Food craving, dietary restraint and mood. Appetite. 1991;17(3):187–97.

White MA, Whisenhunt BL, Williamson DA, Greenway FL, Netemeyer RG. Development and validation of the food-craving inventory. Obes Res. 2002;10(2):107–14. https://doi.org/10.1038/oby.2002.17.

Stoeckel LE, Kim J, Weller RE, Cox JE, Cook EW 3rd, Horwitz B. Effective connectivity of a reward network in nonobese adults. Med Sci Sports Exerc. 2017;49(11):2268–75. https://doi.org/10.1249/ MSS.0000000000001368.
36. Drummen M, Dorenbos E, Vreugdenhil ACE, Raben A, Westerterp-Plantenga MS, Adam TC. Insulin resistance, weight, and behavioral variables as determinants of brain reactivity to food cues: a prevention of diabetes through lifestyle intervention and population studies in Europe and around the World - a PREVIEW study. Am J Clin Nutr. 2019;109(2):315–21. https://doi.org/10.1093/ajcn/nqy252. Using data from the Horizon 2020 PREVIEW study the authors measured fasting glucose and glucose tolerance as potential mechanisms to explain food compared to non-food brain activation and physical activity levels.

37. Baecke JA, Burema J, Frijters JE. A short questionnaire for the measurement of habitual physical activity in epidemiological studies. Am J Clin Nutr. 1982;36(5):936–42. https://doi.org/10.1093/ajcn/36.5.936.

38. Horner KM, Finlayson G, Byrne NM, King NA. Food reward in active compared to inactive men: roles for gastric emptying and body fat. Physiol Behav. 2016;160:43–9. https://doi.org/10.1016/j.physbeh.2016.04.009.

39. Killgore WD, Kipman M, Schwab ZJ, Tkachenko O, Peep L, Gogel H, et al. Physical exercise and brain responses to images of high-calorie food. Neuroreport. 2013;24(17):962–7. https://doi.org/10.1097/wnr.0b013e32832e0229.

40. Luo S, O’Connor SG, Belcher BR, Page KA. Effects of physical activity and sedentary behavior on brain response to high-calorie food cues in young adults. Obesity (Silver Spring). 2018;26(3): 540–6. https://doi.org/10.1002/oby.22107. Tested the interaction between BMI status and physical activity on neuronal activation to high-calorie foods and showed that inverse associations were stronger in young adults with obesity.

41. Oustric P, Myers A, Gibbons C, Buckland N, Dalton M, Long C, et al. Are objectively measured free-living physical activity and sedentary behavior associated with control over eating and food preferences in women? Appetite. 2018;123:465. https://doi.org/10.1016/j.appet.2017.11.067.

42. Alkahtani SA, Byrne NM, Hills AP, King NA. Acute interval exercise reduces reward for high-fat food in adults with overweight/obesity. Med Sci Sports Exerc. 2019.

43. Beaulieu K, Hopkins M, Gibbons C, Oustric P, Caudwell B, Blundell JE, et al. Exercise training reduces reward for high-fat food in adults with overweight/obesity. Med Sci Sports Exerc. 2019.

44. Beaulieu K. The influence of physical activity level on the sensitivity of the appetite control system. Leeds: University of Leeds; 2017.

45. Cornier MA, Melanson EL, Salzberg AK, Bechtell JL, Tregellas JR. The effects of exercise on the neuronal response to food cues. Physiol Behav. 2012;105(4):1028–34.

46. Finlayson G, Caudwell B, Hopkins M, King N, Blundell JE. Low fat loss response after medium-term supervised exercise in obese is associated with exercise-induced increase in food reward. J Obes. 2011;2011:615624. https://doi.org/10.1155/2011/615624.

47. Martin CK, Johnson WD, Myers CA, Apolzan JW, Earnest CP, Thomas DM, et al. Effect of different doses of supervised exercise on food intake, metabolism, and non-exercise physical activity: the E-MECHANIC randomized controlled trial. Am J Clin Nutr. 2019. https://doi.org/10.1093/ajcn/nqz054.

48. Geiselman PJ, Anderson AM, Dowdy ML, West DB, Redmond SM, Smith SR. Reliability and validity of a macronutrient self-selection paradigm and a food preference questionnaire. Physiol Behav. 1998;63(5):919–28. https://doi.org/10.1006/phbe.1997.0078.

49. Finlayson G, Caudwell B, Hopkins M, King N, Blundell JE. Interval training reduces reward for high-fat food in adults with overweight/obesity. Med Sci Sports Exerc. 2019.

50. Alkahtani SA, Byrne NM, Hills AP, King NA. Acute interval exercise reduces reward for high-fat food in adults with overweight/obesity. Med Sci Sports Exerc. 2019.

51. Thivel D, Fillon A, Genin PM, Miguel M, Khammassi M, Pereira B, et al. Satiety responsiveness but not food reward is modified in response to an acute bout of low versus high intensity exercise in healthy adults. Appetite. 2019;145:104500. https://doi.org/10.1016/j.appet.2019.104500.

52. Saanijoki T, Nummenmaa L, Tuurali JJ, Tuominen L, Arponen E, Kallikoski KK, et al. Aerobic exercise modulates anticipatory reward processing via the mu-opioid receptor system. Hum Brain Mapp. 2018;39(10):3972–83. https://doi.org/10.1002/hbm.24224.

53. Alkahtani SA, Byrne NM, Hills AP, King NA. Interval training intensity affects energy intake compensation in obese men. Int J Sport Nutr Exerc Metab. 2014;24(6):595–604.

54. Alkahtani SA, Byrne NM, Hills AP, King NA. Interval training intensity affects energy intake compensation in obese men. Int J Sport Nutr Exerc Metab. 2014;24(6):595–604.

55. Alkahtani SA, Byrne NM, Hills AP, King NA. Interval training intensity affects energy intake compensation in obese men. Int J Sport Nutr Exerc Metab. 2014;24(6):595–604.

56. Martin CK, Johnson WD, Myers CA, Apolzan JW, Earnest CP, Thomas DM, et al. Effect of different doses of supervised exercise on food intake, metabolism, and non-exercise physical activity: the E-MECHANIC randomized controlled trial. Am J Clin Nutr. 2019. https://doi.org/10.1093/ajcn/nqz054.

57. Finlayson G, Caudwell B, Hopkins M, King N, Blundell JE. Low fat loss response after medium-term supervised exercise in obese is associated with exercise-induced increase in food reward. J Obes. 2011;2011:615624. https://doi.org/10.1155/2011/615624.

58. Martin CK, Johnson WD, Myers CA, Apolzan JW, Earnest CP, Thomas DM, et al. Effect of different doses of supervised exercise on food intake, metabolism, and non-exercise physical activity: the E-MECHANIC randomized controlled trial. Am J Clin Nutr. 2019. https://doi.org/10.1093/ajcn/nqz054.

59. Geiselman PJ, Anderson AM, Dowdy ML, West DB, Redmond SM, Smith SR. Reliability and validity of a macronutrient self-selection paradigm and a food preference questionnaire. Physiol Behav. 1998;63(5):919–28. https://doi.org/10.1006/phbe.1997.0078.

60. Finlayson G, Caudwell B, Hopkins M, King N, Blundell JE. Low fat loss response after medium-term supervised exercise in obese is associated with exercise-induced increase in food reward. J Obes. 2011;2011:615624. https://doi.org/10.1155/2011/615624.

61. Martin CK, Johnson WD, Myers CA, Apolzan JW, Earnest CP, Thomas DM, et al. Effect of different doses of supervised exercise on food intake, metabolism, and non-exercise physical activity: the E-MECHANIC randomized controlled trial. Am J Clin Nutr. 2019. https://doi.org/10.1093/ajcn/nqz054.

62. Finlayson G, Caudwell B, Hopkins M, King N, Blundell JE. Int J Sport Nutr Exerc Metab. 2014;24(6):595–604.

63. Martin CK, Johnson WD, Myers CA, Apolzan JW, Earnest CP, Thomas DM, et al. Effect of different doses of supervised exercise on food intake, metabolism, and non-exercise physical activity: the E-MECHANIC randomized controlled trial. Am J Clin Nutr. 2019. https://doi.org/10.1093/ajcn/nqz054.

64. Alkahtani SA, Byrne NM, Hills AP, King NA. Interval training intensity affects energy intake compensation in obese men. Int J Sport Nutr Exerc Metab. 2014;24(6):595–604.

65. Alkahtani SA, Byrne NM, Hills AP, King NA. Interval training intensity affects energy intake compensation in obese men. Int J Sport Nutr Exerc Metab. 2014;24(6):595–604.
66 Joseph RJ, Alonso-Alonso M, Bond DS, Pascual-Leone A, Blackburn GL. The neurocognitive connection between physical activity and eating behaviour. Obes Rev. 2011;12(10):800–12. https://doi.org/10.1111/j.1467-789X.2011.00893.x.

67 Annesi JJ, Porter KJ. Behavioural support of a proposed neurocognitive connection between physical activity and improved eating behaviour in obese women. Obes Res Clin Pract. 2014;8(4):e325–30. https://doi.org/10.1016/j.orcp.2013.08.001.

68 Oustric P, Thivel D, Dalton M, Beaulieu K, Gibbons C, Hopkins M, et al. Measuring food preference and reward: application and cross-cultural adaptation of the Leeds Food Preference Questionnaire in human experimental research. Food Qual Prefer. 2020;80:103824. https://doi.org/10.1016/j.foodqual.2019.103824.

69 Hopkins M, Gibbons C, Caudwell P, Webb DL, Hellstrom PM, Naslund E, et al. Fasting leptin is a metabolic determinant of food reward in overweight and obese individuals during chronic aerobic exercise training. Int J Endocrinol. 2014;2014:323728. https://doi.org/10.1155/2014/323728.

70 Rosenbaum M, Kissileff HR, Mayer LES, Hirsch J, Leibel RL. Energy intake in weight-reduced humans. Brain Res. 2010;1350:95–102. https://doi.org/10.1016/j.brainres.2010.05.062.

71 Tremblay A, Dutheil F, Drapeau V, Metz L, Lesour B, Chapier R, et al. Long-term effects of high-intensity resistance and endurance exercise on plasma leptin and ghrelin in overweight individuals: the RESOLVE Study. Appl Physiol Nutr Metab. 2019;44(11):1172–9. https://doi.org/10.1139/apnm-2019-0019.

72 Gibbons C, Blundell JE, Caudwell P, Webb DL, Hellstrom PM, Naslund E, et al. The role of episodic postprandial peptides in exercise-induced compensatory eating. J Clin Endocrinol Metab. 2017;102(11):4051–9. https://doi.org/10.1210/jc.2017-00817.

73 Legget KT, Wylie KP, Cornier MA, Melanson EL, Paschall CJ, Tregellas JR. Exercise-related changes in between-network connectivity in overweight/obese adults. Physiol Behav. 2016;158:60–7. https://doi.org/10.1097/wnb.0000000000000013.

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.