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Reward for fat and sweet dimensions of food are altered by an acute bout of running in healthy young men

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ABSTRACT

Acute moderate- to high-intensity exercise, primarily aerobic exercise, has been reported to decrease food reward in brain regions via the hedonic pathways and reduce preference for high-energy or high-fat foods. However, studies examining food reward responses to acute exercise have been limited to measuring food reward only after exercise and less frequently before and after exercise. Therefore, the changes in food reward in response to acute exercise remain unclear. This study investigated the effect of acute running on food reward in healthy young men. Fourteen young healthy men (mean ± standard deviation, age; 23 ± 2 years, body mass index; 21 ± 2 kg/m^2) completed two trials (i.e., exercise and control) in a randomised, crossover design. Participants performed a 30-min running bout at 70% of maximal oxygen uptake or sitting rest before and after food reward evaluation with a computer-based food choice behaviour task tool. Food reward was assessed for foods varying in fat content and sweet taste, and there were four assessment parameters: explicit liking, explicit wanting, implicit wanting and frequency of choice of each food category (relative preference). Explicit and implicit wanting, and relative preference for high-fat relative to low-fat foods were reduced after the exercise trial compared to the control trial (trial-by-time interaction, all $p \leq 0.02$). Implicit wanting and relative preference for sweet relative to savoury foods were increased after the exercise trial compared to the control trial (trial-by-time interaction, all $p \leq 0.003$). These findings indicate that moderate-intensity acute running alters the reward bias away from high fat towards low fat foods and away from savoury towards sweet foods in healthy young men.

1. Introduction

Appetite is controlled by homeostatic and non-homeostatic mechanisms (Campos et al., 2022). The homeostatic control of appetite is driven by metabolic and visceral feedbacks sensed by the hypothalamus which regulates the maintenance of a constant energy balance in the organism (Lutter et al., 2009). Non-homeostatic control is also called hedonic control and is modulated by the brain's reward system via dopamine and endogenous opioids (Lutter et al., 2009), and in particular by the food reward system, which is manifested by "liking" and "wanting" for specific foods, and provides direction and intensity to the motivation to eat (Finlayson et al., 2012). Liking is defined as the degree of sensory pleasure obtained from foods and controlled by hedonic spots in the mesolimbic system (Berridge et al., 2003), and wanting is the motivation or attraction towards certain foods - these are important components of food behaviour (Finlayson et al., 2012).

Food intake and physical activity are major behavioural components of energy balance, and physical activity has been shown to alter appetite, and influence eating behaviour and food intake (Blundell et al., 2015). The majority of previous studies examining the effect of acute exercise on appetite have been focused mainly on homeostatic

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Abbreviations

CI	Confidence intervals
ES	Effect size
LFPQ	Leeds Food Preference Questionnaire
LFPQ-J	Leeds Food Preference Questionnaire in Japanese
SD	Standard deviation
TFEQ	Three Factor Eating Questionnaire

regulatory aspects (for a review of these, see Dorling et al., 2018). These studies often demonstrate that an acute bout of moderate- or high-intensity exercise (i.e., 65–80% of maximal oxygen uptake), mainly aerobic exercise, is known to reduce subjective appetite after exercise, a phenomenon known as exercise-induced anorexia (Dorling et al., 2018).

To date, nine laboratory-based studies have examined the effects of acute exercise on food reward evaluated by functional magnetic resonance imaging (Crabtree et al., 2014; Evero et al., 2012; Saanijoki et al., 2018; Thackray et al., 2023) or a computer-based task (Alkahtani et al., 2019; Finlayson et al., 2009; McNeil et al., 2015; Thackray et al., 2020; Thivel et al., 2020) in healthy adults. Evero and colleagues showed that an acute bout of cycling decreases neuronal responses of food reward regions in the brain using functional magnetic resonance imaging, suggesting exercise reduces the pleasure of food (liking), incentive motivation to eat (wanting), and anticipation and consumption of food in healthy young men and women (Evero et al., 2012). Similarly, Crabtree and colleagues reported that an acute bout of running suppresses neural responses in food reward regions of the brain when images of high-energy foods were viewed and increases activation when images of low-energy foods were viewed in healthy young men (Crabtree et al., 2014). One study investigating exercise and food reward using the Leeds Food Preference Questionnaire (LFPQ), a computer-based task designed to measure separable processes of liking and wanting for food (Finlayson et al., 2007) demonstrated decreased relative preference for high-fat foods after aerobic exercise (running) and resistance exercise in healthy young men and women (McNeil et al., 2015). In contrast, no effects on post-exercise food reward were found for other exercise modes (downhill running, swimming and cycling) in young healthy individuals (Alkahtani et al., 2019; Thackray et al., 2020; Thivel et al., 2020). Collectively, these studies suggest that aerobic exercise, running in particular, alters the reward system and reduces the preference for high-fat and high-energy foods. Furthermore, although acute exercise often do not lead to acute compensatory responses in energy intake (King et al., 2010), the study on non-homeostatic control of energy intake in response to daily exercise may provide an important implication for the prevention and management of overweight and obesity. However, in the majority of previous studies examining the effects of acute exercise on food preferences, food reward was only evaluated after exercise (Crabtree et al., 2014; Evero et al., 2012; Finlayson et al., 2009; McNeil et al., 2015; Saanijoki et al., 2018; Thackray et al., 2020; Thivel et al., 2020). In such study designs without a pre-exercise measurement, it is not possible to infer pre- and post-exercise changes, if any. Furthermore, to our knowledge, only two studies have examined the effects of "exercise alone", excluding the concomitant effects of consuming food, on food reward (Alkahtani et al., 2019; Thackray et al., 2023).

Therefore, the purpose of the present study was to examine the effect of an acute bout of running on food reward using the LFPQ which can measure liking and wanting separately in healthy young men. The present study hypothesised that the preference for high-fat foods would be supressed after moderate-intensity (i.e., 70% of maximal oxygen uptake) running.

2. Methods

2.1. Ethical approval

The present study was conducted according to the guidelines of the Declaration of Helsinki, and the protocol was reviewed and approved by the Ethics Committee on Human Research of Waseda University (approval number: 2021–209). Fourteen healthy men provided written informed consent to participate in this study. This study was registered in advance with the University Hospital Medical Information Network Center (UMIN), a clinical trial registration system (ID: UMIN000045434).

2.2. Participants

Participants of the present study were recruited between September 2021 and March 2022 through advertisements placed on the campus. Following the study protocol explanation, any potential risks that may arise and written informed consent were obtained from fourteen Japanese (i.e., self-reported ethnicity) healthy young men. The inclusion criteria of the present study were as follows: 1) aged between 20 and 30 years, 2) no medication or supplementation, 3) no major illness, 4) non-smoker, 5) a stable body weight for at least three months before the study and no intention of losing weight during the study or 6) not participating in other studies while they are participating in the present study. The physical characteristics and eating behaviour traits (details in "Three Factor Eating Questionnaire") of the participants are provided in Table 1.

2.3. Screening and preliminary exercise tests

Participants visited the laboratory at least seven days prior to the first main experimental trial to collect baseline data and familiarise themselves with the study procedures. After obtaining consent to participate in this study, anthropometric and arterial blood pressure measurements were assessed under non-fasting conditions. Body mass was measured to the nearest 0.1 kg using a digital scale (TANITA MC780, Tanita Corporation, Tokyo, Japan). Height was measured to the nearest 0.1 cm using a stadiometer (YS-OA, AS One Corporation, Osaka, Japan). Body mass index was calculated as weight in kilogrammes divided by the square of height in metres. Arterial blood pressure was measured from the left arm after 5 min of seated rest by a standard mercury sphygmomanometer (605P; Yagami Co Ltd, Yokohama, Japan). Two consecutive measurements were taken 1 min apart, and the mean of these values was recorded. The Japanese version of the Three Factor Eating Questionnaire (TFEQ) (Adachi et al., 1992) was then completed. Thereafter, a screening test of the Leeds Food Preference Questionnaire in Japanese

Table 1
Physical characteristics and eating behaviour traits of the 14 participants.

Characteristic	
Age (years)	22.5 ± 1.6
Height (m)	1.72 ± 0.07
Body mass (kg)	61.6 ± 6.7
Body mass index (kg/m^2)	20.8 ± 1.7
Systolic blood pressure (mmHg)	111 ± 10
Diastolic blood pressure (mmHg)	71 ± 10
Maximum oxygen uptake (mL/kg/min)	56.5 ± 7.0
Cognitive restraint score	8.4 ± 3.2
Disinhibition score	4.3 ± 1.7
Hunger score	3.8 ± 1.9

Values are mean ± standard deviation.
Note: Cognitive restraint score presents a level of restrained eating evaluated by the Japanese version of the Three Factor Eating Questionnaire (TFEQ). Disinhibition score represents a level of Disinhibition of eating control evaluated by the Japanese version of the TFEQ. Hunger score represents a level of predisposition to hunger evaluated by the Japanese version of the TFEQ.

(LFPQ-J) (Hiratsu et al., 2022), which was developed specifically for the Japanese population, was conducted (details in "Food reward"). The purpose of the screening test was to ask about the names of the 16 foods used in the LFPQ-J, their allergies, whether or not they had ever eaten them and whether or not they were able to eat them. All participants reported that they were familiar with the foods, had eaten the foods and able to eat the foods, and none of them had food allergies to the foods used in the test. After the screening test, the participants practiced the tasks performed on the LFPQ-J. Participants then underwent two preliminary exercise tests performed on a motorised treadmill (Jog Now 700, Technogym, Cesena, Italy). The first test consisted of a 16-min submaximal incremental running test to determine the relationship between running speed and oxygen uptake. Participants performed four 4-min incremental runs starting at speed of 6.0 or 8.0 km/h, depending on their physical activity level (as determined by the initial screening interview and questionnaire). After a 20-min rest (i.e., following completion of the submaximal treadmill test), the participants were asked to complete a maximum oxygen uptake test using an incremental uphill protocol at a constant speed (Taylor et al., 1955). Data generated from these two tests were used to calculate the running intensity (i.e., 70% of maximum oxygen uptake) of the participants for the main trials.

2.4. *Three Factor Eating Questionnaire*

The 51-item TFEQ is a self-assessment tool that measures eating behaviour, which consists of three factors including cognitive restraint, disinhibition and hunger (Stunkard & Messick, 1985). The Japanese version of the TFEQ (Adachi et al., 1992) was used to measure participants' eating behaviour traits in the present study. Although there are no clear criteria provided, a score of $\geq$14 for cognitive restraint, a score of $\geq$14 for disinhibition and a score of $\geq$7 for hunger are considered elevated (Stunkard & Messick, 1985).

2.5. *Standardisation of energy intake and physical activity*

The participants weighed and recorded all food and drinks consumed the day before the first trial and refrained from drinking alcohol during this period. They replicated their energy intake from the day before the first trial on the day before the second trial to ensure that their energy intake was standardised across the trials. Their food diaries were analysed using Excel Eiyoukun Ver 9.0 software (Kenpakusha, Tokyo, Japan) by a registered dietitian to determine their energy intake and the macronutrient content of the foods. The participants were asked to avoid any strenuous exercise for one day before each main trial. They wore a uniaxial accelerometer (Lifecoder-EX; Suzuken Co Ltd, Nagoya, Japan) on their hip to monitor their daily activity objectively during this period. The reliability of this accelerometer was validated against whole body indirect calorimetry (Kumahara et al., 2004). The accelerometer defined 11 levels of activity intensity (0, 0.5 and 1–9), with 0 indicating the lowest intensity and 9 being the highest intensity. A level of 4 corresponds to an intensity of approximately 3 metabolic equivalents (Kumahara et al., 2004). Level of 1–3 corresponds to light physical activity level, 4–6 corresponds to moderate physical activity level, 7–9 corresponds to vigorous physical activity level. On the day before each main trial, they received text messages from a lead researcher asking them to replicate their energy intake and physical activity patterns. Their compliance with replicating each main test condition was checked verbally upon their arrival at the laboratory.

2.6. *Study design and protocol*

Participants completed the two main experimental trials (i.e., exercise and control) in a randomised order. The interval between trials was at least 6 days. A schematic illustration of the study protocol is presented in Fig. 1.

On each trial day, participants reported to the laboratory at 9:00 a.m. after a 10-h overnight fast (except for water). After a 5-min seated rest, resting blood pressure was measured using a digital automatic blood pressure monitor (HEM-1010, Omron Corporation, Kyoto, Japan) in a seated position. A heart rate monitor (POLAR RCX3: Polar Electro) was then fitted and baseline metabolic responses (oxygen uptake, respiratory exchange ratio, fat oxidation rate and carbohydrate oxidation rate) were measured for 15 min in a seated position using a stationary gas analyser (Quark RMR, COSMED, Rome, Italy). Thereafter, subjective appetite using a paper-based questionnaire (Flint et al., 2000) (details in "Subjective appetite") was evaluated followed by the measurement of food reward using the LFPQ-J (Hiratsu et al., 2022) (details in "Food reward"). Then, the participants performed a 30-min run (i.e., from 9:45 to 10:15 a.m.) on a treadmill at a speed eliciting 70% of their maximum oxygen uptake (determined from the preliminary test) in the exercise trial. In the control trial, the participants were asked to sit on a chair in a comfortable position for 30 min from 9:45 to 10:15 a.m. During this 30-min period, oxygen uptake, respiratory exchange ratio, fat oxidation rate, carbohydrate oxidation rate, heart rate and rating of perceived exertion (Borg, 1973) were measured in both trials. Subjective appetite was again evaluated immediately after a 30-min run or rest followed by the measurement of food reward.

2.7. *Food reward*

According to an extensive literature from studies in animals and humans, the food reward system is thought to contain distinguishable psychological or functional components which have been termed "liking" (pleasure/palatability) and "wanting" (incentive salience/motivation) (Alonso-Alonso et al., 2015; Berridge, 1996; Dalton & Finlayson, 2014). Liking is typically understood as the perceived or

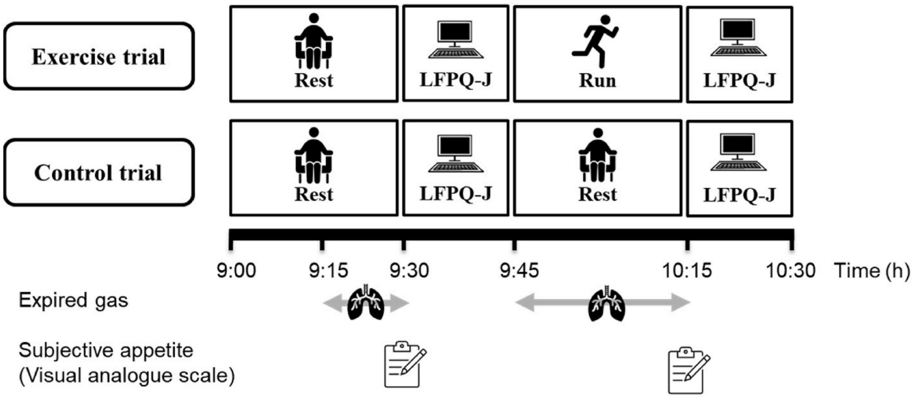

Fig. 1. Schematic representation of the study protocol. LFPQ-J, Leeds Food Preference Questionnaire in Japanese.

expected pleasantness of the taste of a food. Conversely, wanting refers to the attraction that is triggered by the perception of a food or a food-related cue in the environment. By measuring these components separately it is possible to learn under which circumstances they may differ by degree or even become dissociated.

In this study, food reward was measured using the LFPQ-J which is a computer-based task to assess different components of food preference and food reward (Hiratsu et al., 2022). The LFPQ-J measures explicit liking and wanting directly, and implicit wanting indirectly using 16 images of foods that are either high-fat savoury, low-fat savoury, high-fat sweet or low-fat sweet (Hiratsu et al., 2022). The Supplemental Table 1 details the total energy and energy contribution of macronutrients for the 16 food images used. The average energy, protein, fat and carbohydrate content of high-fat food images were 1135.2 kJ/100 g, 13.8%, 52.3% and 34.0%, respectively. The average energy, protein, fat and carbohydrate content of low-fat food images were 325.2 kJ/100 g, 19.8 %, 5.6 % and 74.6 %, respectively. The average energy density and fat content of high-fat foods were higher than the average of low-fat food images. The average carbohydrate content of low-fat food images was higher than the average of high-fat food images. The average energy, protein, fat and carbohydrate content of sweet food images were 790.6 kJ/100 g, 6.3 %, 24.4 % and 69.3 %, respectively. The average energy, protein, fat and carbohydrate content of savoury food images were 669.8 kJ/100 g, 27.3 %, 33.4 % and 39.3 %, respectively. The average energy density and carbohydrate content of sweet foods were higher than the average of savoury food images. The average fat and protein content of savoury food images were higher than the average of sweet food images.

The LFPQ-J consists of two tasks, namely the single foods task and the paired foods task. Food reward was evaluated in terms of four parameters: explicit liking, explicit wanting, implicit wanting and relative preference. In the single foods task, participants were asked to rate each randomly presented food item on a 100-mm visual analogue scale to measure the explicit liking and explicit wanting. Participants responded according to the following two questions, “How pleasant would it be to taste some of this food now?” (explicit liking) and “How much do you want some of this food now?” (explicit wanting), anchored at each end with “not at all” and “extremely”. In the paired food trials, each food image was presented in turn with a food image from another category, and the participants were instructed to select the food they “most want to eat now” as quickly as possible. Implicit wanting was measured from the reaction time of the test and the categories selected, and relative preference was measured from the number of selections per category (Oustric et al., 2020). These food pairs were presented in a total of 96 pairs, such that all food images from one category were presented with each food from the other categories. Implicit wanting was calculated based on the frequency of choice and non-choice, and the reaction time of each task for each food category (Oustric et al., 2020). Bias scores for fat content and taste were computed by subtracting the mean low-fat scores from the mean high-fat scores, and the mean savoury scores from the mean sweet scores, respectively. Positive values indicate a preference for high fat and/or sweet foods, negative values indicate a preference for low fat and/or savoury foods, and a score of 0 indicates an equal preference between fat content and taste categories (Oustric et al., 2020).

2.8. *Subjective appetite*

Subjective appetite was assessed on a 100-mm visual analogue scale (i.e., each end of the line represents the most extreme sensation experienced by the participant) before (9:30 a.m.) and after 30 min of exercise or seated rest (10:15 a.m.) (satiety, fullness, hunger and prospective food intake) (Flint et al., 2000). From the results of the four appetite ratings assessed, an overall subjective appetite score was calculated by the following equation. Satiety + fullness + (100 – hunger) + (100 - prospective food intake)/4 (Gibbons et al., 2019) in which 100 indicates less appetite and 0 indicates more appetite.

2.9. *Statistical analysis*

The hypothesis of the present study and analytical plan were predetermined before the data were collected. Data were analysed with IBM SPSS Statistics for Windows version 28.0 (IBM Corp., Armonk, N.Y., USA). Generalised estimating equations were used to examine between-trial differences for all parameters. Where a significant trial-by-time interaction was found, post-hoc pairwise comparisons were performed with the Bonferroni method. The 95% confidence intervals (95% CI) for the mean absolute pairwise differences between trials were calculated using the t-distribution and degrees of freedom (n - 1). Effect sizes (ES) (Cohen’s d) were calculated to describe the magnitude of difference between trials. Effect sizes of 0.2 are considered the minimum important difference in all outcome measures, 0.5 moderate and 0.8 large (Cohen, 1988). Statistical significance was accepted at the <5% level. Results are reported as the mean ± SD.

3. Results

3.1. *Standardisation of energy intake and physical activity*

All participants reported that they consumed identical foods and drink on the day before the first and second trials. Mean self-reported energy intake for the day prior to each trial was 8.6 ± 2.3 MJ (2064.6 ± 552.5 kcal). Energy intake equated to 12.2 ± 2.8% (62.9 ± 21.1g/day) from protein, 29.6 ± 8.4% (68.1 ± 24.1g/day) from fat and 58.2 ± 9.2% (294.1 ± 86.7 g/day) from carbohydrate.

The total step counts recorded the day before the trials did not differ between the exercise (8162 ± 2345 steps/day) and control (8696 ± 2678 steps/day) trials ($p = 0.512$). Accelerometer recorded frequencies for light-intensity physical activity (exercise: 42.5 ± 21.2 min/day; control: 44.4 ± 15.1 min/day), moderate-intensity physical activity (exercise: 37.8 ± 20.8, control: 45.2 ± 26.6 min/day), vigorous-intensity physical activity (exercise: 3.1 ± 1.9; control: 2.2 ± 1.3 min/day), moderate to vigorous-intensity physical activity (exercise: 40.9 ± 20.7; control: 47.4 ± 26.4 min/day) and total physical activity (exercise: 83.4 ± 33.4; control: 92.1 ± 31.1 min/day) did not differ between the exercise and control trials (all for $p \geq 0.193$).

3.2. *Exercise response*

The mean running speed, heart rate, rating of perceived exertion and gross energy expenditure during the 30-min run were 12.0 ± 1.9 km/h, 162 ± 11 beats/minute, 13.0 ± 1.4 and 1.45 ± 0.18 MJ (347.6 ± 42.6 kcal), respectively. The mean oxygen uptake was 39.4 ± 4.3 mL/kg/min. This corresponded to an exercise intensity of 69.7 ± 2.6 % of maximum oxygen uptake. The mean respiratory exchange ratio was 0.87 ± 0.07. This provided mean percentage of fat oxidation 46.0 ± 18.9 % and carbohydrate oxidation 54.0 ± 18.9 %. In the control trial, the mean heart rate and gross energy expenditure during the 30-min sitting rest were 60 ± 4 beats/minute and 0.18 ± 0.04 MJ (42.6 ± 9.0 kcal), respectively. The mean oxygen uptake was 4.8 ± 1.0 mL/kg/min and the mean respiratory exchange ratio was 0.80 ± 0.04. This provided mean percentage of fat oxidation 68.2 ± 12.4 % and carbohydrate oxidation 31.8 ± 12.4 %.

3.3. *Food reward*

The results of fat appeal bias and taste appeal bias are shown in Figs. 2 and 3, respectively. There were no differences in fat appeal bias scores (high-fat *versus* low-fat foods) pre-intervention (i.e., 9:30 a.m.) between the exercise and control trials for explicit liking (pre-exercise: 4.7 ± 10.4, pre-control: 6.6 ± 11.3), explicit wanting (pre-exercise: 4.8 ± 14.2, pre-control: 5.0 ± 13.4), implicit wanting (pre-exercise: 23.6 ±

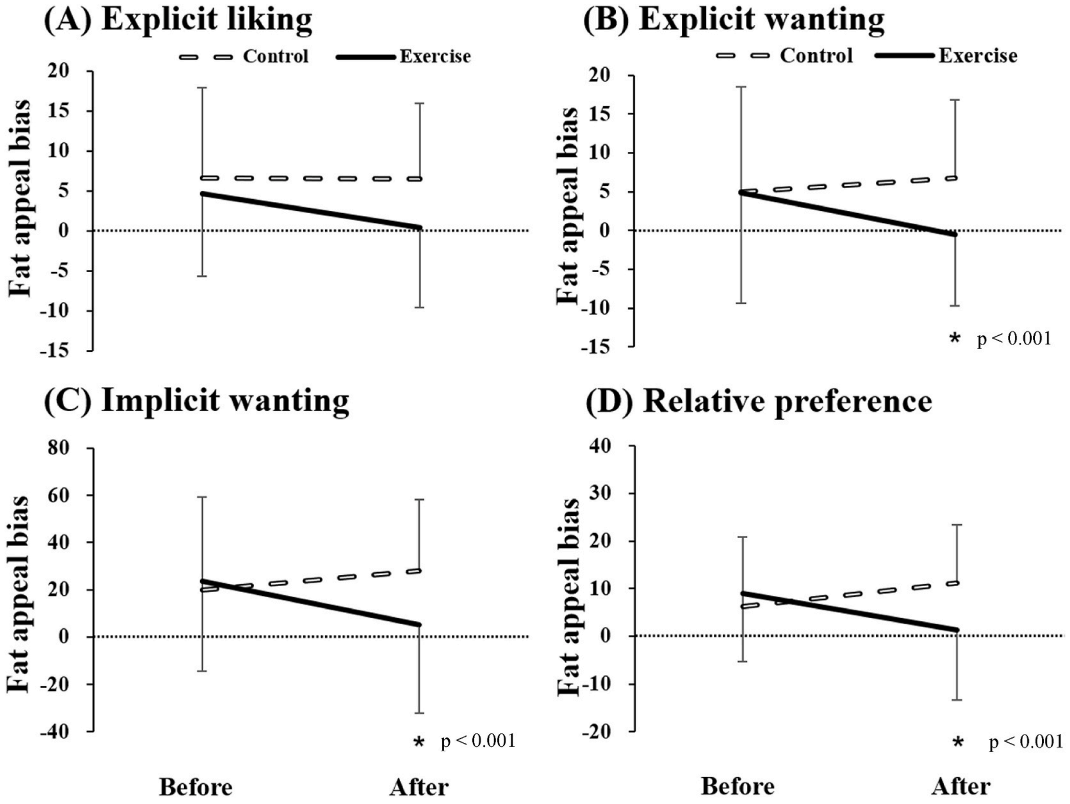

Fig. 2. Pre- and post-run or rest for explicit liking (A), explicit wanting (B), implicit wanting (C) and relative preference (D) of the fat appeal bias between the exercise and control trials. Positive values indicate a relative preference for high fat foods. Negative values indicate a relative preference for low fat foods. A score of 0 indicates an equal preference between fat categories. Mean ± standard deviation. Values were compared using generalised estimating equations. Post-hoc analysis was adjusted for multiple comparisons using the Bonferroni method. *Significantly different from the pre-run time point in the exercise trial. "Before" represents 15 min pre-run or rest. "After" presents 15 min post-run or rest.

38.1, pre-control: 20.0 ± 39.29) or relative preference (pre-exercise: 8.9 ± 14.2, pre-control: 6.2 ± 14.7) (all for $p \geq 0.275$). There was no main effect of trial or trial-by-time interaction for explicit liking in fat appeal bias scores (Fig. 2A). There was a trial-by-time interaction for explicit wanting, implicit wanting and relative preference (all for $p \leq 0.02$). The post-hoc test showed that fat appeal bias scores decreased in the exercise trial post-intervention (i.e., 10:15 a.m.) for explicit wanting (pre-exercise: 4.8 ± 14.2, post-exercise: −0.5 ± 9.2, 95% CI -12.0 to 2.5, $p < 0.01$, ES = 0.76) (Fig. 2B), implicit wanting (pre-exercise: 23.6 ± 38.1, post-exercise: 5.2 ± 37.2, 95% CI -35.6 to −10.2, $p < 0.01$, ES = 0.67) (Fig. 2C) and relative preference (pre-exercise: 8.9 ± 14.2, post-exercise: 1.3 ± 14.7, 95% CI -15.0 to −4.5, $p < 0.01$, ES = 0.72) (Fig. 2D) but remained similar in the control trial ($p > 0.05$ for all).

There were no differences in taste appeal bias scores (sweet *versus* savoury foods) pre-intervention (i.e., 9:30 a.m.) between the exercise and control trials for explicit liking (pre-exercise: −2.8 ± 19.2, pre-control: −5.6 ± 16.0), explicit wanting (pre-exercise: −2.8 ± 17.3, pre-control: −6.5 ± 16.9), implicit wanting (pre-exercise: −17.2 ± 40.4, pre-control: −18.3 ± 43.9) or relative preference (pre-exercise: −6.1 ± 15.3, pre-control: −6.2 ± 15.6) (all for $p \geq 0.368$). There were no main effect of trial or trial-by-time interaction for explicit liking and explicit wanting (Fig. 3A and B). There was a main effect of trial for implicit wanting ($p = 0.02$), and a trial-by-time interaction for implicit wanting and relative preference (both for $p = 0.02$). The post-hoc test showed that taste appeal bias scores increased in the exercise trial post-intervention (i.e., 10:15 a.m.) for implicit wanting (pre-exercise: −17.2 ± 40.4, post-exercise: 10.6 ± 15.6, 95% CI 11.9 to 48.8, $p = 0.001$, ES = 0.85) (Fig. 3C) and relative preference (pre-exercise: −6.1 ± 15.3, post-exercise: 4.6 ± 15.2, 95% CI 4.3 to 20.4, $p = 0.003$, ES = 0.87) (Fig. 3D) but remained similar in the control trial ($p > 0.05$ for all).

3.4. *Subjective appetite*

The subjective appetite measured before and after 30 min of run or rest is shown in Table 2. There were no differences in hunger, satiety, fullness, prospective food intake or overall appetite score pre-intervention (i.e., 9:30 a.m.) between the exercise and control trials (all for $p \geq 0.261$). There was a difference in the pattern of response between trials in hunger, satiety, fullness, prospective food intake and overall appetite score (trial-by-time interaction, hunger: $p = 0.007$, satiety: $p = 0.004$, fullness: $p = 0.027$, prospective food intake: $p = 0.004$ and overall appetite scores: $p < 0.001$). Subsequent post-hoc tests of the interaction showed that hunger and prospective food intake were lower in the exercise trial compared to the control trial post-intervention (i.e., 10:15 a.m.) (hunger: 95%CI -29.1 to 3.2, $p = 0.014$, ES = 0.59, prospective food intake: 95%CI -35.1 to −4.4, $p = 0.012$, ES = 0.74). Satiety, fullness and the overall subjective appetite scores were higher in the exercise trial compared to the control trial post-intervention (i.e., 10:15 a.m.) (satiety: 95%CI 3.1 to 36.4, $p = 0.02$, ES = 0.76, fullness: 95%CI 5.0 to 30.1 $p = 0.006$, ES = 0.61 and overall appetite scores: 95% CI 7.1 to 29.6, $p = 0.001$, ES = 0.91).

4. Discussion

This study assessed the food reward response to an acute moderate-intensity running bout compared with a sitting rest. It included a validated measure of food reward before and after exercise and was able to isolate the effect of the exercise alone without influence from consumption of a test meal post-exercise. The main findings of the present study in healthy young men were as follows: 1) decreased explicit wanting, implicit wanting and relative preference for high-fat relative to

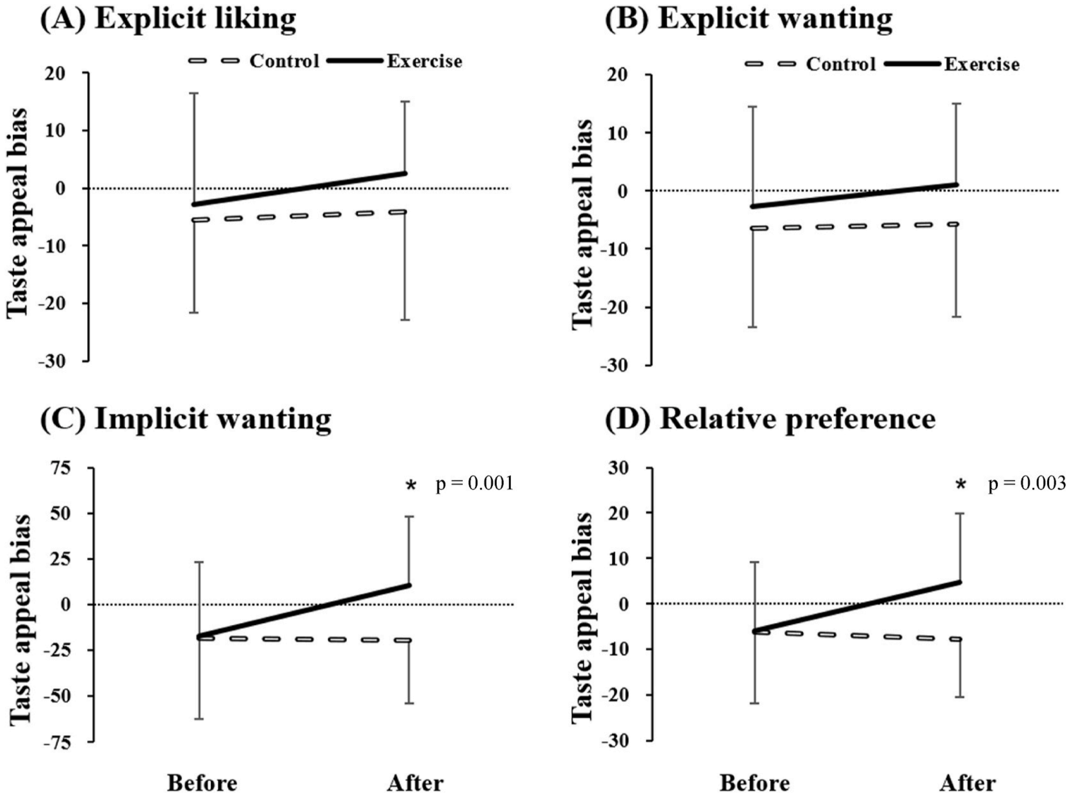

Fig. 3. Pre- and post-run or rest for explicit liking (A), explicit wanting (B), implicit wanting (C) and relative preference (D) of the taste appeal bias between the exercise and control trials. Positive values indicate a relative preference for sweet foods. Negative values indicate a relative preference for savoury foods. A score of 0 indicates an equal preference between taste categories. Mean ± standard deviation. Values were compared using generalised estimating equations. Post-hoc analysis was adjusted for multiple comparisons using the Bonferroni method. *Significantly different from the pre-run time point in the exercise trial. "Before" represents 15 min pre-run or rest. "After" represents 15 min post-run or rest.

low-fat foods were observed after exercise and 2) increased implicit wanting and relative preference for sweet relative to savoury foods were observed after exercise. These findings suggest that an acute bout of running alters the reward bias away from high fat towards low fat foods and away from savoury towards sweet foods.

The present study showed that explicit wanting, implicit wanting and relative preference for fat appeal bias were reduced after a 30-min moderate-intensity run. These findings are similar to a previous study reporting lowered relative preference for high-fat foods after 30 min of moderate-intensity aerobic and resistance exercise, compared with an equivalent time point of a 30-min rest in healthy young adults (McNeil et al., 2015). Furthermore, a study of 60 min of moderate-intensity swimming and cycling also reported there was a tendency toward lowered implicit wanting for fat appeal bias measured only after exercise compared to resting conditions (Thackray et al., 2020). Collectively, the results of the present study that measures food reward before and after exercise extend previous findings (McNeil et al., 2015) by demonstrating an acute about of running exercise alters sub-components of food reward in healthy young men. More specifically, acute exercise reduces both explicit and implicit wanting for high-fat foods. These findings suggest that acute flat running exercise may alter food reward for high-fat foods. It is worth noting that the low-fat food images used in this study also contained more than twice as much carbohydrate as the high-fat food images. Thus, the lowered relative preference for high-fat foods after exercise observed in the present study may have been influenced by increasing appeal for carbohydrate. In addition, the high-fat food images used in this study were more than three times as energy dense as the low-fat food images. It is possible that the lowered relative preference for high-fat foods after exercise observed in the present study may have been influenced by decreasing in reward value of energy dense/rich foods. In contrast, other previous studies have demonstrated that there were no changes in liking or wanting for high-fat foods after cycling of different intensities and eccentric (i.e., downhill) running in healthy young adults (Alkahtani et al., 2019; Thivel et al., 2020). In addition, one study where healthy women performed 50 min of moderate-intensity cycling reported an increase in implicit wanting for high-fat foods in the group that compensated for the energy expended in exercise at the subsequent *ad libitum* test meal, compared to the group that did not compensate (Finlayson et al., 2009). This study suggested that the effect of exercise on food reward may be influenced by individual differences (Finlayson et al., 2009). In addition, the present study demonstrated that implicit wanting and relative preference for taste appeal bias increase after exercise, indicating exercise may increase unconscious wanting and food choice for sweet foods. In contrast, to our knowledge, acute exercise has been reported to have no effect on foods with different taste appeals in healthy individuals as measured by the LFPQ (Alkahtani et al., 2019; McNeil et al., 2015; Thackray et al., 2020; Thivel et al., 2020). Previous studies using the LFPQ have evaluated food reward after exercise under fed conditions (Alkahtani et al., 2019; McNeil et al., 2015; Thackray et al., 2020; Thivel et al., 2020). It has been demonstrated that taste and fat appeal biases for each of explicit liking, explicit wanting and implicit wanting were altered in the fed state compared with the fasted state in healthy young men and women (Hiratsu et al., 2022; Oustric et al., 2020). Therefore, the findings of the previous studies (Alkahtani et al., 2019; McNeil et al., 2015; Thackray et al., 2020; Thivel et al., 2020) may have been influenced by pre-exercise feeding status, making it difficult to evaluate the influence of exercise alone on taste changes, if any. Well-controlled studies examining the effect of acute exercise on food reward are limited in the current literature, and therefore more various aspects of acute exercise studies, including different exercise modes, populations and timings of assessment on food reward are needed to be examined in future studies.

Table 2
Subjective appetite measured before and after 30 min of run or rest in the exercise and control trials.

			p		
	Before	After	Trial	Time	Trial-by-time interaction
Hunger					
Exercise	74.1 ± 22.2	58.0 ± 30.3 [a b]	0.006	0.184	0.007
Control	73.5 ± 24.8	82.1 ± 24.3 [c]			
Satiety					
Exercise	21.2 ± 12.9	41.0 ± 29.9 [a b]	0.444	0.044	0.004
Control	26.9 ± 21.8	22.6 ± 22.9 [c]			
Fullness					
Exercise	24.2 ± 28.1	41.8 ± 29.7 [a b]	0.024	0.128	0.027
Control	23.5 ± 19.9	17.8 ± 22.9 [c]			
Prospective food intake					
Exercise	73.0 ± 19.1	53.2 ± 30.8 [a b]	0.023	0.135	0.004
Control	70.6 ± 22.1	77.9 ± 22.5 [c]			
Overall appetite score					
Exercise	24.6 ± 15.6	42.9 ± 27.3 [a b]	0.030	0.034	$p < 0.001$
Control	26.6 ± 20.6	20.1 ± 22.1[c]			

Values are means ± standard deviation. Values are compared using generalised estimating equations and post-hoc analysis was adjusted for multiple comparisons using the Bonferroni method.

[a] Significantly different between trials at the same point, $p \leq 0.027$.

[b] Significantly different between before and after run (i.e., within-trial), $p \leq 0.02$.

[c] Significantly different between before and after rest (i.e., within-trial), $p \leq 0.04$.

Some studies examining the effect of acute exercise on food reward also used functional magnetic resonance imaging, which can assess reward system-related regions of the brain. A previous study showed that an acute bout of high-intensity cycling resulted in a reduced function of the reward system-related regions in the insula, putamen and orbitofrontal cortex in food images and the regions responsible for pleasure in food, motivation to eat and anticipation, and consumption of food, compared to rest in physically active men (Evero et al., 2012). Similarly, there was a reduction in neural responses in reward system-related regions, including the orbitofrontal cortex and hippocampus in food images after high-intensity running in moderately active men (Crabtree et al., 2014). In particular, the orbitofrontal cortex and hippocampus showed reduced neural responses in high-energy food images (Crabtree et al., 2014). On the other hand, increased neural responses in the putamen and insula were observed in low-energy food images (Crabtree et al., 2014). Although it is not possible to compare directly, these findings are similar to the findings of the present study using the LFPQ-J, in which explicit wanting, implicit wanting and relative preference in fat appeal bias decreased after acute running exercise, and preference switched from high-fat foods to low-fat foods. Therefore, it is speculated that aerobic exercise may have reduced the explicit and implicit wanting for high-fat foods and food choices observed in the present study by reducing neural responses in reward system-related areas. Indeed, the previous study has reported that high-intensity aerobic exercise reduced the neural response in the pallidum, which is involved in motivating food intake, when viewing high-energy food images compared to low-energy food images, and these alterations correlated with subjective thirst (Crabtree et al., 2014). These findings may suggest that post-exercise hedonic regulation is influenced by the water content of foods. In the present study, this may have been influenced by the relatively higher water content of some low-fat foods, such as udon noodles and radish salad, compared with high-fat foods. Alternatively, an acute bout of running elicits aversion to high energy foods due to reduced subjective appetite as this was the case in the present study. Although no direct functional magnetic resonance imaging studies in response to exercise have been reported to date on foods with different tastes, Saanijoki and colleagues showed that reward system regions when presented with images of palatable and unpalatable foods after moderate-intensity cycling were inversely correlated with changes in the endogenous opioid receptor system but no changes in reward system-related regions between foods were found (Saanijoki et al., 2018). Regarding the phenomenon of increased preference and wanting for sweet foods after exercise, a systematic review study summarising changes in taste perception with exercise and sweet solutions reported an increase in preference for sweetness after acute exercise (Gauthier et al., 2020). This increase in preference for sweet taste may have been caused as a result of changes in carbohydrate utilisation and energy balance due to exercise affecting food choice and preference (Hopkins et al., 2011). To support this notion, in the present study, the estimated relative contribution of total carbohydrate oxidation to the total energy expenditure after running was 54.0 ± 18.9 %, indicating that more carbohydrate was oxidised than at an equivalent time point during the rest (31.8 ± 12.4 %), which may have increased preference and food choice for sweeter foods containing more carbohydrate as described in Supplemental Table 1.

In the present study, an acute bout of moderate-intensity running for 30 min decreased subjective hunger and prospective food intake while acute running increased satiety and fullness compared with rest, indicating an overall appetite suppression. These results are consistent with findings from previous studies reporting that a brief suppression of subjective appetite is often observed after performing acute aerobic exercise at intensities above 60% of peak oxygen uptake in healthy young men (Dorling et al., 2018). Although the mechanisms by which acute exercise temporarily suppresses subjective appetite are not fully explained in the present study, it has been reported that appetite-related hormones may be involved in appetite suppression after exercise, with lowered concentrations of acylated ghrelin, and increased concentrations of peptide tyrosine-tyrosine and glucagon-like peptide 1 (Dorling et al., 2018). However, these exercise-induced changes in subjective appetite and appetite-related hormones are not always observed in parallel as appetite regulation is influenced by a complex interaction of physiological and psychological factors (Thackray & Stensel, 2023). Subjective feelings of appetite such as hunger and satiety are considered as homeostatic appetite variables and are thought to interact with the reward system, hedonic appetite, via the orbitofrontal cortex (Rolls, 2005). Therefore, changes in subjective appetite may have been influenced by the changes in food reward, or vice versa. On the other hand, although previous empirical studies have reported a decrease in subjective appetite after acute aerobic exercise, no correlation was found between neural responses in the reward system area and subjective appetite, and no association was also reported between brain activity and subjective appetite (Crabtree et al., 2014; Evero et al., 2012; Thackray et al., 2023). How changes in subjective appetite sensations in response to exercise influence food reward remains to be fully understood, as are the mechanisms underlying the observed effects on food reward. Therefore, the relevance of homeostatic and non-homeostatic appetite control should be investigated comprehensively to corroborate exercise-induced short-term appetite modulations.

The present study has several strengths. Most previous studies examining the effect of acute exercise on food reward have measured food reward only during a post-exercise period in a postprandial state (Alkahtani et al., 2019; Crabtree et al., 2014; Evero et al., 2012; Finlayson et al., 2009; McNeil et al., 2015; Saanijoki et al., 2018; Thackray et al., 2020; Thivel et al., 2020). In contrast, the present study is the first to examine pre- and post-exercise changes in food reward by assessing it with the LFPQ-J and examine the effect of acute exercise alone on food reward. In addition, only three (Alkahtani et al., 2019; Thackray et al., 2020, 2023) out of nine previous studies have controlled for physical activity and diet on the previous day (Alkahtani et al., 2019; Crabtree et al., 2014; Evero et al., 2012; Finlayson et al., 2009; McNeil et al., 2015; Saanijoki et al., 2018; Thackray et al., 2020, 2023; Thivel et al., 2020). In the present study, we controlled the diet and physical activity of participants on the previous day and the day of the experiment, eliminating any potential influences on food reward. There are some limitations to the present study. First, the study only assessed food reward on a computer-based test and did not evaluate actual eating behaviour with subsequent *ad libitum* test meals. A previous meta-analysis examining the effect of acute exercise on energy intake demonstrates that acute exercise does not increase or decrease the absolute energy intake measured immediately or up to a few hours post-exercise (Schubert et al., 2013). Whether similar absolute energy intake exists using different composition of foods provided at *ad libitum* test meals (i.e., different conditions) has not been explored but represents an important future research direction. In addition, the present study did not measure neural responses in reward system-related areas or appetite-related hormones in response to acute exercise. Furthermore, the present study was conducted with young healthy men and this limits the generalisability of our findings to other different age groups and sexes, and health conditions (Beaulieu et al., 2020). Indeed, in a previous study conducted in male and female individuals with overweight and obesity, an increase in attentional bias towards food cues was observed after an acute bout of exercise using an arm-leg elliptical ergometer (Flack et al., 2022). Moreover, the same research group has also demonstrated that food reward was increased after a 12-week aerobic exercise training in inactive men and women, particularly in those who lost fat free mass, highlighting the importance of fat free mass maintenance in exercise-induce weight loss programmes (Flack et al., 2020). Finally, the smaller, non-significant, effect of exercise on explicit liking may be attributed to differences in the interpretation of the question wording by the participants. With our question wording specifying ‘How pleasant would it be to taste some of this food now?’ it is feasible that some participants may have interpreted this more broadly as the enjoyment of eating and some more narrowly as the pleasantness of the taste in the mouth, which could have affected the clarity of the exercise-induced explicit liking outcomes observed in our study.

5. Conclusion

In conclusion, acute moderate-intensity running altered food reward via decreased explicit wanting, implicit wanting and preference for high-fat relative to low-fat foods, and increased implicit wanting and preference for sweet relative to savoury foods in healthy young men. These findings provide important insights into the pre- and post-exercise changes in food reward and highlight important avenues for future long-term research on the non-homeostatic regulation of appetite in response to exercise.

Ethical statement

The present study was conducted according to the guidelines of the Declaration of Helsinki, and the protocol was reviewed and approved by the Ethics Committee on Human Research of Waseda University (approval number: 2021–209). Fourteen healthy men provided written informed consent to participate in this study. This study was registered in advance with the University Hospital Medical Information Network Center (UMIN), a clinical trial registration system (ID: UMIN000045434).

CRediT authorship contribution statement

Yoshiki Yamada: Writing – original draft, Formal analysis, Data curation. **Ayano Hiratsu:** Formal analysis, Data curation. **David Thivel:** Writing – review & editing, Supervision. **Kristine Beaulieu:** Writing – review & editing, Supervision. **Graham Finlayson:** Writing – review & editing, Supervision. **Chihiro Nagayama:** Formal analysis, Data curation. **Kayoko Kamemoto:** Formal analysis, Data curation. **Sirikul Siripiyavatana:** Formal analysis, Data curation. **Yusei Tataka:** Formal analysis, Data curation. **Miki Sakazaki:** Formal analysis, Data curation. **Masashi Miyashita:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors have no conflict of interest to disclose with respect to this work.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.appet.2024.107562.

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