An acute bout of swimming increases post-exercise energy intake in young healthy men and women

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1. Introduction

The interaction between exercise and appetite control is an important issue which holds relevance for energy balance and weight management (Blundell, Gibbons, Caudwell, Finlayson, & Hopkins, 2015; Stensel, 2011). Over the last twenty years, many research groups have scrutinised how exercise, of various forms, impacts on appetite perceptions, *ad libitum* energy intake and appetite-related hormones (Dorling et al., 2018). The consensus of this research is that single bouts of moderate- to high-intensity exercise transiently suppress appetite, but do not influence subsequent *ad libitum* energy intake on the day exercise is performed (Deighton & Stensel, 2014; Schubert, Desbrow, Sabapathy, & Leveritt, 2013). This knowledge supports a therapeutic role of exercise in weight control given its ability to induce an energy deficit without eliciting compensation, at least in the short term.

An understanding of the relationship between exercise and appetite control has been derived from studies employing predominantly land-based forms of exercise, most notably running and cycling. This fact is relevant because anecdotal (Burke, 2007), and preliminary experimental data (King, Wasse, & Stensel, 2011), suggests that swimming may stimulate appetite and energy intake. This contention is supported by the findings from two studies showing that water-based exercise (submerged cycling) stimulated post-exercise energy intake (Dressendorfer, 1993; White, Dressendorfer, Holland, McCoy, & Ferguson, 2005). Direct investigations of appetite and energy intake responses to acute swimming have demonstrated that swimming had no effect on post-exercise energy intake (King, Wasse, & Stensel, 2011; Lambert, Flynn, Braun, Boardley, 1999), but evoked a weaker satiety response to a post-exercise meal (King, Wasse, & Stensel, 2011). Unfortunately, these studies are limited by the inclusion of small, male only samples; and the lack of a true control trial (resting) along with a matched land-based exercise trial. The latter represents an essential study design feature, to isolate the effects of swimming from exercise *per se*.

In recent years, the interaction between exercise and the hedonic value of food has received increasing attention from the scientific community (Berthoud, 2011; Finlayson & Dalton, 2012). That is, researchers have been interested to determine whether exercise may alter the perceived or expected pleasure-giving value of food along with the motivation to consume certain foods. These factors have been conceptualised as ‘liking and wanting’ and can be assessed using the Leeds Food Preference Questionnaire (LFPQ) (Dalton & Finlayson, 2014). Research examining the acute effects of exercise on liking and wanting of foods has thus far produced mixed findings. Specifically, some studies have indicated that aerobic and resistance exercise decrease the relative preference for high-fat vs. low-fat foods (McNeil, Cadieux, Finlayson, Blundell, & Doucet, 2015), whereas other studies suggest no impact of various forms of exercise on reward-related parameters (Alkahtani, Aldayel, & Hopkins, 2019; Martins et al., 2015; Thivel et al., 2020). Given previous evidence hinting that water-based exercise may stimulate a drive to eat, it is possible that swimming may influence appetite-related reward parameters, but further work is required to investigate this hypothesis empirically.

The primary aim of this study was to directly compare the acute effects of exertion-matched swimming and cycling on appetite, energy intake, and food preference and reward in men and women. As a secondary exploratory aim, we sought to determine the modulating effect of sex on key study outcomes. Based on existing evidence, our primary hypothesis was that swimming, but not cycling, would increase appetite, *ad libitum* energy intake and the motivation and preference to consume high-fat and sweet foods.

2. Methods

2.1. Ethical approval and participants

This study received approval from Loughborough University's Research Ethics Committee (R17-P059) before any trial-related procedures commenced. Seventeen healthy men and 15 healthy women (total $n = 32$) were recruited from the local community and provided written informed consent to participate. To avoid awareness of the research aims affecting key study outcomes, information sheets provided to participants stated that the study sought to examine the impact of exercise on mood, stress and arousal. Participants were debriefed about the true aims of the study after the final experimental trial. Participants were: young adults (aged < 40 years), without obesity (body mass index < 30 kg/m^2) and did not smoke or possess diagnosed metabolic health conditions. Participants were habitually active and able to swim and cycle at a recreational level (not elite). Participants reported being weight stable (< 2 kg body mass change) in the three months before the study. All female participants reported being eumenorrheic and not pregnant. Table 1 provides details of the participants who completed the study.

2.2. Pre-assessment and familiarisation

Participants attended the laboratory on one occasion before the main trials to permit the collection of baseline data and to be familiarised with important study procedures. Measurements of stature and body mass were made using an integrated stadiometer and scale (285, Seca GmbH & Co.KG, Germany), whilst body fat percentage was estimated using bio-electrical impedance analysis (BC-418, Tanita, UK). Participants subsequently completed the Three Factor Eating Questionnaire (Stunkard AJ & Messick S, 1985) and were familiarised with the 100 mm visual analogue (appetite) scales (Flint, Raben, Blundell, & Astrup, 2000), the LFPQ (Dalton & Finlayson, 2014), rating of perceived exertion scale (Borg, 1973), exercise procedures and the *ad libitum* test meal. Notably, participants were familiarised with the entire *ad libitum* test meal procedure. Acceptability of the meal was subsequently confirmed by ensuring that a ‘reasonable’ amount of food had been consumed, and secondly, through participant dialogue.

2.3. Study design and procedures

Participants completed three main experimental trials (swimming, cycling, control) in a crossover fashion, with the order of trials being randomised. Because a single bout of exercise can affect energy intake for up to three days later (Rocha, Paxman, Dalton, Winter, & Broom, 2013), an interval of at least four days separated each main experimental trial. For women, all trials occurred during the follicular phase (days 1 – 7) of the menstrual cycle. Figure 1 provides a schematic overview of the study design.

On the morning of each main trial, participants consumed a breakfast meal at 08:45 in their own home. This meal was prepared by the research team and provided to participants in advance. Compliance with the timing of this meal was confirmed by the research team. Participants subsequently arrived at the research centre at 10:00 where they remained until the end of the experimental trial. In the control trial, participants rested in the laboratory for the trial duration. Between 10:30 (0 h) and 11:30 (1 h), five-min expired gas samples were collected into Douglas bags every 15 min to permit the calculation of resting energy expenditure and substrate oxidation via indirect calorimetry (Frayn, 1983). At 11:45 (1.25 h), participants sat in a room in isolation where they completed the LFPQ on a laptop. At 12:00 (1.5 h), participants were provided with access to a homogeneous pasta meal which they were free to consume *ad libitum* until 12:30 (2 h). Participants subsequently rested in the laboratory for one additional hour (until 13:30). The purpose of this final hour, which included no additional study procedures, was to reduce the likelihood that participants would not eat to ‘comfortable satiety’ at the *ad libitum* meal, because of the impending opportunity to consume more desirable foods, or to engage in social eating opportunities, once outside of the laboratory.

Identical procedures were undertaken in the swimming and cycling trials except that 60 min exercise protocols were undertaken between 10:30 (0 h) and 11:30 (1 h). Swimming was undertaken at the institution’s swimming pool (25 m) adjacent to the research laboratory, whilst cycling was completed on a stationary ergometer (Lode Excalibur, Lode B.V., The Netherlands) in the same laboratory where participants rested. In both exercise trials, the exercise protocols consisted of six, eight min intervals of exercise separated by two min of rest. The interval nature of the protocol was chosen to more closely resemble the intermittent pattern of leisure activity which is often performed by recreational swimmers. To match the moderate- to high-intensity exercise stimulus between swimming and cycling, participants were asked to work at a self-reported target rating of perceived exertion (RPE) (Borg, 1973) of 15 (‘hard’) during the exercise intervals. Heart rate was measured continuously by short-range telemetry (T31 Polar Electro Ltd, Warwick, UK) as an objective assessment of exercise intensity. In the swimming trial, participants were free to choose their stroke for each interval and rested between intervals whilst stood in the pool at the end of the lane. The average speed of swimming was assessed by monitoring the distance accumulated in each interval. In the cycling trial, participants self-selected their power output in the first 20 seconds of each interval and then continued at that exercise intensity for the remainder of the interval. Participants rested between intervals whilst sat stationary on the cycle ergometer. The average power output for each interval was recorded by the research team.

2.4. Physical activity and dietary standardisation

Participants recorded all food and drink consumed in the 24 h preceding the first experimental trial, which was replicated in the 24 h before subsequent trials. Participants were required to consume their habitual diet during this period to ensure adequacy of endogenous carbohydrate stores. Alcohol, caffeine and structured physical activity were not permitted within this same 24 h standardisation period. Participants arrived at the laboratory via the same mode of transport for each main trial having fasted from 22:00 the previous evening. Participants living within one mile walked slowly to the laboratory, whilst those living further away arrived via motorised transport.

2.5. Appetite and environmental conditions

Subjective perceptions of hunger, fullness, satisfaction and prospective food consumption (PFC) were measured using 100 mm appetite scales at five strategically determined time-points during main trials (0 h [pre-exercise/rest], 1 h [post-exercise/rest], 1.25 h [pre-LFPQ], 1.5 h [pre *ad libitum* meal], 2 h [post *ad libitum* meal]). These questions were interspersed with 100 mm scales relating to mood, stress and arousal as part of the blinding process within the study. Environmental temperature and humidity were measured during exercise or rest (0–1 h) using a handheld hygrometer (Omega RH85, UK). The temperature of the swimming pool was measured using a glass thermometer (Fisher Scientific, UK).

2.6. Study meals

The standardised breakfast provided to study participants consisted of a strawberry jam sandwich, croissant and orange juice (69% carbohydrate, 22% fat and 9% protein). This contained 2720 kJ for men and 2200 kJ for women, which based on our previous research, provided 25% of daily (sex-specific) energy requirements (Alajmi et al., 2016; King, Wasse, Ewens, et al., 2011). *Ad libitum* energy intake was assessed from a homogeneous meal containing pasta, tomato sauce and olive oil (72% carbohydrate, 12% protein, 16% fat, 6.5 kJ per gram). These ingredients were combined in advance of trials and the meal was reheated before serving to participants. Consumption of individual macronutrients was determined by calculating the amount of energy consumed from each macronutrient and then dividing that value by the energy equivalent for carbohydrate (17 kJ/g), fat (37 kJ/g) and protein (17 kJ/g). Participants were provided with access to the meal for 30 min and were instructed to eat until ‘comfortably full and satisfied’. Participants ate the meal in a room with no external influences and were required to self-serve from a large bowl containing an amount of pasta in excess of expected consumption (~1 kg cooked pasta). The mass of food consumed was determined by subtracting the mass of food remaining (including leftovers) from that initially presented. Absolute energy intake was deduced using nutritional information provided by the food manufacturers. Relative energy intake was calculated for the swimming and cycling trials by subtracting the net energy expenditure of exercise from the absolute energy intake during the homogenous meal.

2.7. Leeds Food Preference Questionnaire

At 11:45 (1.25 h) in all trials, participants completed the LFPQ which is a validated laptop-based procedure that measures food preference and reward (Finlayson, King, & Blundell, 2008). The LFPQ provides measures of wanting and liking for an array of food images which vary in fat content and taste. The conduct and analysis of this questionnaire have been described in depth previously (Dalton & Finlayson, 2014). In brief, sixteen different food items, spanning four categories (high-fat savoury, low-fat savoury, high-fat sweet, low-fat sweet) were employed. To obtain the measurement of ‘relative preference’, participants were required to select the food they ‘most want to eat now’ from paired combinations presented simultaneously. Implicit wanting was ascertained by examining the reaction time for these choices, adjusted for frequency of choice for each category. Explicit liking and explicit wanting were determined by asking participants to rate the extent to which they ‘liked’ or ‘wanted’ each randomly presented food item with a 100 mm visual analogue scale. Bias scores for fat appeal and sweet appeal were ascertained by subtracting the low-fat scores from the high-fat scores and then savoury scores from the sweet scores, respectively.

2.8. Exercise energy expenditure

During the final minute of each cycling interval, a 60 s collection of expired gases was obtained using Douglas bags to permit the assessment of energy expenditure using indirect calorimetry. Specifically, the Haldane transformation was used to calculate inspired gas volumes and to determine oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) (Wilmore & Costill, 1973). Stoichiometric equations were then used to determine absolute quantities of fat ($1.67 \times \dot{V}O_2 - 1.67 \times \dot{V}CO_2$) and carbohydrate ($4.55 \times \dot{V}CO_2 - 3.21 \times \dot{V}O_2$) oxidised (assuming negligible protein oxidation) (Frayn, 1983). Total energy expenditure was subsequently determined by multiplying oxidised substrates by 39 and 17 kJ/gram, respectively.

For each swimming interval, participants were free to choose their stroke, however, the selected stroke had to be maintained for the entire interval. The energy expenditure elicited during each swimming interval was estimated using Metabolic Equivalents (METs) specific to the swimming stroke and speed: recreational breaststroke (5.3 METs), recreational backstroke (4.8 METs), slow front crawl (≤ 0.95 m/s; 5.8 METs), fast front crawl (> 0.95 m/s; 9.8 METs) (Ainsworth et al., 2019). Total exercise-related energy expenditure during swimming was derived by summing the energy expenditure for each exercise interval. The net energy expenditure of each exercise mode was determined by subtracting each participants' resting energy expenditure (during control) from the gross exercise-induced energy expenditure.

2.9. Statistical analyses

Data were analysed using the software package IBM SPSS Statistics for Windows version 24.0 (IBM Corporation, New York, USA). Appetite perceptions are presented and analysed relative to baseline (0 h) values (delta). Time-averaged total area under the curve for delta appetite perceptions were calculated using the trapezoidal method. The model residuals for all outcome variables were explored using histograms. All variables were deemed to show parity to a Gaussian distribution and are presented as mean ± SD.

Linear mixed models were used to examine between trial (swimming vs. cycling) differences in exercise responses. Energy and macronutrient intakes, baseline (0 h) and delta area under the curve for appetite perceptions, and food preference and reward scores were examined using linear mixed models with trial (control, cycling, swimming) modelled as the sole fixed effect. Differences in delta appetite perceptions over time were explored using linear mixed models with trial (control, cycling, swimming) and time (0, 1, 1.25, 1.5 and 2 h) modelled as fixed effects. An exploratory analysis was conducted for all outcomes with sex modelled as a fixed effect and with a sex-by-trial interaction term. All models were adjusted for the period effect to account for any change in responses over time irrespective of trial (Senn, 1993).

Absolute standardised effect sizes (ES) were calculated to supplement important findings and thresholds of 0.2, 0.5, and 0.8 describe small, moderate, and large effects, respectively (Cohen, 1989). Mean differences and the respective 95% confidence intervals (95% CI) are presented. Exact P values (to 3 decimal places) are reported except for very small values which are displayed as $P < 0.001$. Interpretation of the data is based on the 95% CI and ES rather than more conventional dichotomous hypothesis testing (Wasserstein et al., 2019).

3. Results

3.1. Exercise responses

During the 48 min of swimming, the mean distance completed was 1,543 ± 393 m at an average speed of 0.54 ± 0.14 m/s. To complete the swimming sessions, some participants maintained a single stroke (front crawl *n* = 7; breaststroke *n* = 11; backstroke *n* =1) whereas others used a combination of front crawl, breaststroke and backstroke (n = 13). During cycling, a mean power output of 121 ± 38 watts was completed.

The 95% CI for the mean difference in heart rate elicited during swimming and cycling overlapped zero (146 ± 15 vs. 143 ± 18 beats/min, respectively; ES = 0.20, 95% CI -1, 8 beats/min, P = 0.085). Mean RPE was marginally higher during swimming than cycling (15.2 ± 0.7 vs. 14.9 ± 0.6, respectively; ES = 0.52, 95% CI 0.1, 0.6, P = 0.005), whereas estimated net energy expenditure was lower during swimming than cycling (1088 ± 286 vs. 1684 ± 580 kJ, respectively; ES = 1.30, 95% CI -820, -387 kJ, P < 0.001).

3.2. Energy intake

A main effect of trial was identified for absolute (P = 0.017) and relative (P < 0.001) energy intake (Table 2). Swimming increased absolute energy intake compared to control (ES = 0.47, P = 0.005), whereas the magnitude of increase was smaller after cycling compared to control (ES = 0.31, P = 0.062) (Figure 2A, Table 2). The difference in absolute energy intake between swimming and cycling was trivial (ES = 0.16, P = 0.324) (Figure 2A, Table 2). Relative energy intake (absolute energy intake minus the net energy expenditure of exercise) was lower than control in the swimming (ES = 0.39, P = 0.045) and cycling (ES = 1.02, P < 0.001) trials.

Relative energy intake was higher in the swimming trial than the cycling trial (ES = 0.63, P = 0.001) (Table 2).

3.3. Ratings of perceived appetite

Ratings of perceived hunger, fullness, satisfaction and PFC were similar across trials at baseline (0 h) (all P ≥ 0.422) (Table 3). A main effect of trial was identified for delta hunger (P < 0.001), fullness (P = 0.039) and PFC (P = 0.001) but not satisfaction (P = 0.309), but no trial-by-time interactions were observed (all P ≥ 0.352) (Figure 3). Delta hunger and PFC were higher and delta fullness was lower than control in the swimming (all ES ≥ 0.20, P ≤ 0.017) and cycling (all ES ≥ 0.16, P ≤ 0.051) trials; the two exercise trials were similar (all ES ≤ 0.15, P ≥ 0.082). The area under the curve for delta appetite perceptions were similar across trials (all P ≥ 0.106) (Table 3, Figure 3).

3.4. Food preference and reward

Fat and sweet appeal bias scores for relative preference, explicit wanting and explicit liking, and sweet appeal bias scores for implicit wanting were similar across trials (all P ≥ 0.080) (Table 4). The main effect of trial for implicit wanting fat appeal bias was not statistically significant (P = 0.055), but values were lower in the cycling compared to the control (ES = 0.25, P = 0.035) and swimming (ES = 0.24, P = 0.038) trials (Table 4). The difference in implicit wanting fat appeal bias between the swimming and control trial was trivial (ES = 0.00, P = 0.973) (Table 4).

3.5. Exploratory analyses

Exploratory analysis revealed no main effect of sex for swimming distance (men 1,509 ± 376 m, women 1,582 ± 420 m; ES = 0.18, 95% CI -361, 214 m, P = 0.606) or average swim speed (men 0.52 ± 0.13 m/s, women 0.55 ± 0.15 m/s; ES = 0.19, 95% CI -0.13, 0.07 m/s, P = 0.597).

Mean cycling power output was higher in men than women (men 139 ± 40 watts, women 100 ± 22 watts; ES = 1.19, 95% CI 15, 63 watts, P = 0.002). Estimated net energy expenditure was, on average, 280 kJ higher in men than women irrespective of exercise mode (ES = 0.64, 95% CI 49, 511 kJ, P = 0.020), but a trial-by-sex interaction was not apparent (P = 0.273) (data not shown).

An exploratory analysis with sex modelled as a fixed effect and with a trial-by-sex interaction term revealed higher absolute energy intake in men (Figure 2B) than women (Figure 2C) (mean difference: 1042 kJ; ES = 0.68, 95% CI -1, 2085 kJ, P = 0.050). Men exhibited higher perceived appetite at baseline (0 h) than women for hunger (mean difference: 13 mm; ES = 0.46, 95% CI 1, 25 mm, P = 0.040) and PFC (mean difference: 14 mm; ES = 0.57, 95% CI 1, 27 mm, P = 0.033). Sweet appeal bias scores were higher in men than women for explicit liking (mean difference: 19 mm; ES = 0.89, 95% CI 4, 35 mm, P = 0.018), explicit wanting (mean difference: 20 mm; ES = 0.86, 95% CI 4, 37 mm, P = 0.019), and implicit wanting (mean difference: 34 AU; ES = 0.85, 95% CI 5, 63 AU, P = 0.023).

Modelling sex as a fixed effect revealed no other main effects of sex ($P \geq 0.069$) or any trial-by-sex interactions ($P \geq 0.092$) and did not alter interpretation of the main effects of trial or trial-by-time interactions outlined previously when sex was omitted from the models.

4. Discussion

The consensus from previous research suggests that single bouts of exercise do not elicit compensatory increases in appetite and energy intake in the hours afterwards (Dorling et al., 2018; Schubert et al., 2013). The interaction between exercise, appetite and energy intake has been investigated predominantly using land-based forms of exercise, such as running and cycling. Given preliminary evidence suggesting that swimming may augment appetite and energy intake (Burke, 2007; King, Wasse, & Stensel, 2011), this study specifically examined the impact of swimming on appetite, energy intake, and food preference and reward. Importantly, responses to swimming were directly compared with an exertion-matched cycling bout so that the influence of swimming could be distinguished from the effects of exercise *per se*. In contrast to previous literature, our results show that a single bout of swimming increased *ad libitum* energy intake at a meal consumed shortly after exercise. This effect was consistent between men and women and the absolute increase was higher than that observed in the cycling trial compared to control. Furthermore, this outcome was unrelated to food preference or reward, which were largely unresponsive to both exercise modalities.

Two previous studies demonstrated no effect of a single bout of swimming on *ad libitum* energy intake at meals consumed shortly after exercise (King, Wasse, & Stensel, 2011; Lambert, Flynn, Braun, Boardley, 1999). This finding, which contrasts the results from the present study, likely relates to procedural differences between studies. For instance, Lambert et al (1999) studied a small group of highly trained triathletes who completed 45 min bouts of vigorous-intensity (72% of maximum oxygen uptake) swimming and running. Participants' habituation to swimming, and energy turnover more broadly, may have masked the responses that we have seen in individuals swimming, but not at a competitive level. Another relevant disparity is the method used to assess *ad libitum* energy intake. In both previous studies, energy intake was assessed from buffet style meals. Conversely, in the present study we implemented a single item homogeneous meal because it is now recognised that homogeneous test meals provide greater sensitivity to detect between-trial differences given the smaller variance in outcome and reduced predisposition to overconsumption (Horner, Byrne, & King, 2014; King et al., 2017). Relating to this latter point, it is notable that across the exercise and rest trials, energy intake was considerably greater (26-58%) in the previous studies (King, Wasse, & Stensel, 2011; Lambert, Flynn, Braun, Boardley, 1999) compared with the present investigation. This may have blunted the ability to test for differences between conditions in the previous experiments.

Anecdotally, it has been suggested that swimming increases appetite (Burke, 2007); and in our previous experimental study, swimming elicited a weaker satiety response, verses a resting control trial, at a meal consumed one hour post-exercise (King, Wasse, & Stensel, 2011). In the present study, participants reported being hungrier and less full throughout the swimming trial in comparison to control. A similar response was witnessed in the cycling trial, although visually this difference was apparent earlier in the swimming trial i.e. by the end of exercise. The augmented appetite in response to swimming was consistent with our hypothesis; however, we did not expect cycling to elicit a similar response. High-intensity exercise is typically associated with appetite suppression and, therefore, the moderate- to high-intensity of exercise undertaken in this study is likely to have had a permissive effect on appetite perceptions. Interestingly, PFC was marginally higher in response to swimming vs. cycling. This finding is consistent with the proportionally greater increase in energy intake after swimming (vs. control) than cycling.

In a meta-analysis of 51 acute studies, it was concluded that exercise has a trivial effect on energy intake consumed at meals within two hours after exercise cessation (Schubert et al., 2013). This data highlights the uniqueness of our findings when comparing the results to previous evidence. In seeking to explain our novel outcome, it is relevant to note that energy expenditure is unlikely to be explanative. This is because energy expenditure was estimated to be higher on the cycling verses swimming trial. Instead, water immersion and associated changes in body temperature, are perhaps the most likely explanation for the stimulatory effect of swimming on post-exercise energy intake. This suggestion is supported by data showing that energy intake was increased after treadmill-based exercise undertaken in cool (8-10^{o}C) vs. neutral ambient temperatures (Crabtree & Blannin, 2015; Wasse, King, Stensel, & Sunderland, 2013); and after cycling submerged in cold (20–22^{o}C) vs. thermoneutral water (Dressendorfer, 1993; White et al., 2005). In the present study, the water temperature was 28 ± 1^{o}C which is lower than thermoneutral for humans (34–35^{o}C) (Craig & Dvorak, 1966). Consequently, although swimming would have generated metabolic heat, it is likely that participants' prolonged contact with cool water would lead to net body heat loss. This has been theorised to be an important driver of food intake in homeotherms (Brobeck, 1948).

The precise mechanisms by which heat loss and/or cool water exposure augment energy intake are not clear and were beyond the scope of the present study. We have previously shown that swimming did not influence circulating levels of the hunger stimulating gut hormone, acylated ghrelin (King, Wasse, & Stensel, 2011). However, others have shown that cold exposure reduces circulating leptin and its signalling within central appetite circuits (Reynés et al., 2017; Zeyl, Stocks, Taylor, & Jenkins, 2004). This response could theoretically prompt an increase in energy intake and provides an interesting hypothesis for future experiments.

Given the importance of non-homeostatic influences governing appetite and food intake, a key purpose of this study was to explore the potential impact of swimming on food preference and reward. Using functional magnetic resonance imaging, running and cycling have previously been shown to suppress hedonic responses to food cues in key reward-related brain regions

(Crabtree, Chambers, Hardwick, & Blannin, 2014; Evero, Hackett, Clark, Phelan, & Hagobian, 2012). Furthermore, when employing the LFPQ, others have shown that aerobic and resistance exercise reduce the explicit liking and relative preference for high fat vs. low fat foods (McNeil et al., 2015). In contrast to our original hypothesis, food preference and reward were largely unresponsive to both swimming and cycling. A tendency for cycling to reduce implicit wanting fat appeal bias scores compared with swimming and control was the only documented finding in our analyses. Taken collectively, these findings support the conclusions of others who have suggested that the pattern of food reward is stable in the context of acute exercise (Martins et al., 2015). In the present study it should be recognised that our sample size was not powered specifically to assess the effect of exercise on food preference and reward. However, it is notable that our sample size was twice that utilised by McNeil et al. (2015) who had sufficient power to detect differences in exercise related LFPQ outcomes. Speculatively, given the similarity in participants examined and trial procedures, it is possible that the higher intensity of the exercise protocols employed by McNeil et al. (2015) explains the discrepant outcome i.e. food preference and reward may be affected more by higher-intensity exercise. Nonetheless, given the large variability in responses observed, our data indicates that recreational bouts of moderate- to high-intensity exercise, with and without water immersion, have no consistent impact on food preference or reward (assessed via the LFPQ).

Given the potential for sex-based differences in appetite control and energy homeostasis (Hagobian & Braun, 2010), we investigated the moderating effect of sex on study outcomes. Overall, our analyses showed that sex did not modulate the key outcomes of this study. Consequently, we can be confident that the key messages from our research can be generalised to both men and women. This sensitivity analysis revealed that men tended to consume more energy than women; however, this was consistent across trials. One interesting finding to emerge from the LFPQ data was that men demonstrated a greater implicit wanting, and explicit wanting and liking, for sweet vs. savoury foods, in comparison to women. Again, however, this was consistent across trials and additional studies are needed to determine the consistency of this finding.

The present study has some notable strengths and limitations which should be recognised. A key strength of our study was that it included a large sample that was almost equally composed of men and women. This has enabled us to explore the potential for sex-based interactions within our data. The importance of this is underscored by the recognition that women have traditionally been underrepresented in many aspects of health-based research (Feldman et al., 2019); particularly relating to energy balance where menstrual standardisation is necessary. Limitations include the short duration of the observation period which restricts the ability to discern whether the impact of swimming on energy intake is enduring and likely to influence energy balance meaningfully over the long-term. In a holistic sense, the stimulatory effect of swimming on energy intake was relatively small (~598 kJ) and it is unclear whether this difference would be augmented or negated at subsequent post-exercise meals. Additionally, for practical reasons, our study did not include a non-exercise, water immersion trial, and therefore it is not possible to determine whether the influence of swimming on energy intake was due to an interaction between exercise and water immersion, or water immersion *per se*. Finally, it should be noted that energy expenditure in the swimming trial was estimated using METs whereas direct measurements (indirect calorimetry) were undertaken in the cycling trial. Relative energy intake data, specifically within the swimming trial, should therefore be viewed with caution. Future studies should strive to obtain more precise measures of energy expenditure during swimming which can be directly measured using modified indirect calorimetry apparatus (Rodríguez, Keskinen, Kusch, & Hoffmann, 2008).

In conclusion, a single bout of moderate- to high-intensity swimming increased *ad libitum* energy intake in a sample of recreationally active men and women. The magnitude of increase after swimming (vs control) was greater than that observed after an exertion-matched cycling trial (vs control), which contributed to a greater relative energy intake after swimming. This response does not appear to be related to differences in food preference or reward. Additional studies are needed to characterise the longer-term influence of swimming on appetite and energy intake and to define the acute orexigenic mechanism(s).

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Author contributions

JAK, DJS, AET, LJJ, DRB and, DJC conceived the study idea. JAK, GSF, SW, JAS, MD and AS performed data collection. AET and JAK conducted the data analysis and led the writing of the manuscript. All authors reviewed and approved the final version of the manuscript.

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Figure legends

Figure 1. Schematic representation of the main trial protocol. Arrow indicates participants arrival at the laboratory, chequered rectangle indicates standardised breakfast, white rectangles indicate swimming, cycling or rest (control), grey rectangle indicates the Leeds Food Preference Questionnaire, and black rectangle indicates *ad libitum* pasta meal.

Figure 2. Absolute *ad libitum* energy intake in the control (■), cycling (●) and swimming (△) trials in (A) all participants combined (*n* = 32), (B) male participants only (*n* = 17) and (c) female participants only (*n* = 15). Data points represent individual data values and the black solid line indicates the mean ± SD. Panel A: main effect of trial $P = 0.017$ (cycling vs. control $P = 0.062$; swimming vs. control $P = 0.005$; swimming vs. cycling $P = 0.324$). Panels B and C: main effect of sex $P = 0.050$; trial-by-sex interaction $P = 0.967$.

Figure 3. Delta ratings of perceived (A) hunger, (B) fullness, (C) satisfaction and (D) prospective food consumption (PFC) in the control (■), cycling (●) and swimming (△) trials in 17 men and 15 women. Data points on left hand figures represent mean ± SEM. White rectangle indicates swimming, cycling or rest (control), grey rectangle indicates Leeds Food Preference Questionnaire, and black rectangle indicates *ad libitum* pasta meal. Main effect of trial: hunger $P < 0.001$, fullness $P = 0.039$, satisfaction $P = 0.309$, PFC $P = 0.001$. Data points on right hand panels represent individual data points for time-averaged total area under the curve and the black solid line represents the mean ± SD. Main effect of trial all $P \geq 0.106$.

Table 1. Participant characteristics.

	All (n = 32)	**Men (n = 17)**	**Women (n = 15)**	**Main effect of sex Men vs. women Mean difference (95% CI)[1]**
Age (years)	23 ± 2	24 ± 2	22 ± 3	2 (-0.1, 3)
Stature (m)	1.71 ± 0.08	1.76 ± 0.08	1.65 ± 0.04	0.11 (0.07, 0.15)[2]
Body mass (kg)	70.7 ± 12.8	77.9 ± 12.6	62.4 ± 6.6	15.5 (8.1, 22.9)[2]
Body mass index (kg/m^2)	24.0 ± 2.6	25.0 ± 2.6	22.8 ± 2.3	2.1 (0.4, 3.9)[2]
Body fat (%)	19.9 ± 7.3	14.8 ± 4.5	25.8 ± 5.1	-11.0 (-14.5, -7.5)[2]
Lean body mass (kg)	56.7 ± 12.3	66.1 ± 9.1	46.1 ± 3.3	20.0 (14.9, 25.0)[2]
Three Factor Eating Questionnaire				
Dietary restraint	9 ± 5	8 ± 5	9 ± 5	-1 (-4, 2)
Dietary disinhibition	6 ± 2	6 ± 3	6 ± 2	0 (-2, 2)
Hunger	6 ± 3	6 ± 3	6 ± 3	0 (-2, 2)

Values are mean ± SD. Data were analysed using linear mixed models with sex (men or women) included as a fixed factor.

[1] Mean difference and 95% confidence interval of the mean absolute difference between men and women.

[2] Main effect of sex $P \leq 0.018$.

Table 2. *Ad libitum* energy and macronutrient intakes in the control, cycling and swimming trials.

	Control	**Cycling**	**Swimming**	**Mean difference (95% CI)**[1]		
				Cycling vs. control	**Swimming vs. control**	**Swimming vs. cycling**
Absolute energy intake (kJ)	3259 ± 1265	3652 ± 1619	3857 ± 1611	392 (-21, 805)	598 (185, 1010)[3]	205 (-207, 618)
Relative energy intake (kJ)	3259 ± 1265	1967 ± 1675	2769 ± 1610	-1277 (-1742, -812)[2]	-475 (-940, -10)[3]	802 (337, 1267)[4]
Protein (g)	23 ± 9	26 ± 12	28 ± 12	3 (-0.1, 6)	4 (1, 7)[3]	1 (-1, 4)
Carbohydrate (g)	140 ± 54	157 ± 70	166 ± 69	17 (-1, 35)	26 (8, 43)[3]	9 (-9, 27)
Fat (g)	14 ± 5	16 ± 7	16 ± 7	2 (-0.1, 3)	3 (1, 4)[3]	1 (-1, 3)

Values are mean ± SD for *n* = 32. Data were analysed using linear mixed models with trial (control, cycling or swimming) included as a fixed factor and with adjustment for the period effect. A main effect of trial was identified for absolute energy, relative energy and macronutrient intakes ($P \leq 0.017$).

[1] Mean difference and 95% confidence interval of the mean absolute difference between the experimental trials adjusted for the period effect.

[2] Cycling vs. control $P < 0.001$.

[3] Swimming vs. control $P \leq 0.045$.

[4] Swimming vs. cycling $P = 0.001$.

Table 3. Baseline and time-averaged total area under the curve for appetite perceptions in the control, cycling and swimming trials.

	Control	Cycling	Swimming	Mean difference (95% CI)[1]		
				Cycling vs. control	**Swimming vs. control**	**Swimming vs. cycling**
Baseline (0 h)						
Hunger (mm)	33 ± 23	29 ± 20	29 ± 24	-5 (-13, 3)	-4 (-12, 4)	0 (-7, 8)
Fullness (mm)	55 ± 25	60 ± 17	57 ± 22	5 (-4, 14)	2 (-7, 11)	-3 (-12, 6)
Satisfaction (mm)	57 ± 19	58 ± 20	60 ± 18	1 (-6, 8)	3 (-4, 10)	2 (-5, 9)
PFC (mm)	42 ± 23	40 ± 22	39 ± 22	-2 (-10, 6)	-3 (-11, 5)	-1 (-9, 7)
Time-averaged total area under the curve						
Delta hunger (mm h)	9.2 ± 10.1	13.6 ± 15.8	16.7 ± 15.5	4.4 (-2.5, 11.4)	7.5 (0.5, 14.4)	3.0 (-3.9, 10.0)
Delta fullness (mm h)	-5.3 ± 15.4	-8.2 ± 16.0	-10.0 ± 17.2	-2.9 (-10.1, 4.3)	-4.7 (-11.9, 2.5)	-1.8 (-9.0, 5.4)
Delta satisfaction (mm h)	-2.8 ± 11.2	-0.4 ± 12.0	-1.3 ± 15.1	2.4 (-3.5, 8.3)	1.5 (-4.4, 7.4)	-0.9 (-6.8, 5.0)
Delta PFC (mm h)	5.8 ± 12.4	8.8 ± 17.0	12.8 ± 12.5	3.0 (-3.8, 9.9)	7.0 (0.2, 13.9)	4.0 (-2.9, 10.9)

Values are mean ± SD for *n* = 32. Data were analysed using linear mixed models with trial (control, cycling or swimming) included as a fixed factor and with adjustment for the period effect. Linear mixed models revealed no main effects of trial ($P \geq 0.106$). PFC, prospective food consumption.

[1] Mean difference and 95% confidence interval of the mean absolute difference between the experimental trials adjusted for the period effect.

Table 4. Measures of relative preference, implicit wanting, explicit wanting and explicit liking assessed 15 minutes after 60 minutes of exercise (cycling and swimming) or rest (control).

	Control	**Cycling**	**Swimming**	**Mean difference (95% CI)[1]**		
				Cycling vs. control	**Swimming vs. control**	**Swimming vs. cycling**
Relative preference						
Fat appeal bias (AU)	-4.0 ± 11.0	-1.8 ± 10.8	-4.0 ± 9.5	2.2 (-0.5, 4.9)	0.1 (-2.6, 2.7)	-2.2 (-4.8, 0.5)
Sweet appeal bias (AU)	-0.3 ± 16.0	0.8 ± 14.5	0.3 ± 15.4	1.1 (-2.5, 4.7)	0.6 (-3.0, 4.2)	-0.5 (-4.1, 3.2)
Implicit wanting						
Fat appeal bias (AU)	12.9 ± 33.0	4.7 ± 37.6	12.7 ± 30.9	-8.2 (-15.8, -0.6)	-0.1 (-7.7, 7.5)	8.0 (0.5, 15.6)
Sweet appeal bias (AU)	-1.9 ± 43.0	3.8 ± 39.4	2.2 ± 41.0	5.7 (-4.8, 16.3)	4.1 (-6.5, 14.7)	-1.6 (-12.2, 8.9)
Explicit wanting						
Fat appeal bias (mm)	2.7 ± 10.9	1.2 ± 14.8	6.2 ± 12.8	-1.5 (-6.0, 2.9)	3.4 (-1.0, 7.9)	5.0 (0.5, 9.4)
Sweet appeal bias (mm)	-1.0 ± 27.8	0.4 ± 22.1	-2.2 ± 20.6	1.4 (-3.9, 6.7)	-1.1 (-6.4, 4.2)	-2.6 (-7.8, 2.7)
Explicit liking						
Fat appeal bias (mm)	2.7 ± 9.8	0.6 ± 14.9	4.4 ± 12.7	-2.1 (-6.2, 1.9)	1.7 (-2.4, 5.8)	3.8 (-0.3, 7.9)
Sweet appeal bias (mm)	-2.4 ± 24.6	2.0 ± 21.9	0.2 ± 20.7	4.3 (-0.8, 9.4)	2.6 (-2.6, 7.7)	-1.7 (-6.9, 3.4)

Values are mean ± SD for $n = 32$. Data were analysed using linear mixed models with trial (control, cycling or swimming) included as a fixed factor and with adjustment for the period effect. Linear mixed models revealed no main effects of trial ($P \geq 0.055$).

[1] Mean difference and 95% confidence interval of the mean absolute difference between the experimental trials adjusted for the period effect.