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Virtual reality exergaming improves affect during physical activity and reduces subsequent food consumption in inactive adults

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ABSTRACT

An individual's affective (i.e. emotional) response to exercise may play an important role in post-exercise eating behaviour for some individuals. Taking advantage of advances in fully immersive virtual reality (VR) technology, this study aimed to: a) examine whether VR exergaming can improve the psychological response to exercise in inactive adults, and b) assess the extent to which this improvement reduces post-exercise appetite and eating behaviour. In a cross-over study, 34 adults not meeting the World Health Organisation's physical activity recommendations completed two exercise sessions on a stationary bike; one while engaging in a VR exergame and one without VR. Monitoring enabled heart rate, energy expenditure, and duration across conditions to be closely matched. The Physical Activity Enjoyment Scale, Feeling Scale, Felt Arousal Scale and Borg's Ratings of Perceived Exertion were measured to capture the affective responses to exercise. Appetite and eating behaviour were evaluated using visual-analogue scales, a computerised food preference task, and intake at a post-exercise buffet meal. Cycling in VR elicited greater exercise enjoyment ($p < 0.001$, $\eta^2p = 0.62$), pleasure ($p < 0.001$, $\eta^2p = 0.47$), and activation ($p < 0.001$, $\eta^2p = 0.55$). VR exergaming did not alter perceived physical exertion ($p = 0.64$), perceived appetite ($p = 0.68$), and preference for energy dense ($p = 0.78$) or sweet/savoury foods ($p = 0.90$) compared to standard exercise. However, it did result in a mean 12% reduction in post-exercise food intake (mean difference: 105.9 kcal; $p < 0.01$; $\eta^2p = 0.20$) and a decrease in relative food intake ($p < 0.01$; $\eta^2p = 0.20$), although inter-individual differences in response to VR exergaming were observed. The integration of VR in a cycling workout improves the affective experience of physical activity for inactive adults and reduces subsequent food intake. Virtual reality technology shows potential as an adjunct tool to support adults in weight management programmes become more active, especially for those individuals who are prone to eat in excess after physical activity.

1. Introduction

Health benefits of regular physical activity include improved muscular and cardiorespiratory fitness, bone and functional health, insulin sensitivity, and healthy weight control (Kohl et al., 2012). Given its importance for the prevention and treatment of noncommunicable diseases such as obesity, the World Health Organisation (WHO) has developed a Global Action Plan to reduce worldwide physical inactivity (WHO, 2018). In some countries, physical activity has been promoted via the introduction of national policies and schemes, but uptake and long-term adherence to these programmes is often poor (Biddle & Batterham, 2015; Pavey et al., 2012).

In relation to weight management programmes, a separate concern is that participation in physical activity can result in overeating in some individuals (King et al., 2007; Werle et al., 2015), which could subsequently interfere with weight loss attempts (Cawley, 2011; Drenowatz, 2015; King et al., 2007). Eating behaviour after a bout of moderate intensity physical activity, however, does not appear to be underpinned by an automatic biological necessity to restore energy balance (Hall et al., 2011; Melanson et al., 2013; Rogers & Brunstrom, 2016). There is extensive evidence against an increase in energy intake to compensate for exercise-induced exergy expenditure (Rocha et al., 2018; Schubert et al., 2013). Rather, accruing evidence suggests that post-exercise eating behaviour is driven by the valuation of effort exerted to engage in physical activity and the cognitive 'licencing' of increased energy

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Nomenclature

VR	Virtual Reality
WHO	World Health Organisation
PACES	Physical Activity Enjoyment Scale
PRETIE-Q:	Preference for and Tolerance of the Intensity of Exercise Questionnaire;
VAS	Visual Analogue Scale
SF-36|	Short Form-36
TFEQ-18	Three-Factor Eating Questionnaire-18
FAS	Felt Arousal Scale
FS	Feeling Scale
RPE	Rating of Perceived Exertion
MVPA	Moderate-to-Vigorous Physical Activity
EE	Energy Expenditure

intake as a form of compensation (Martins et al., 2007; McCaig et al., 2016; Werle et al., 2011). In line with this view, individuals who experience a negative affective response to physical activity (i.e. high levels of distress, fatigue, low enjoyment, autonomy and perceived competence), have been shown to eat more after exercise when the activity is labelled as 'fat-burning' (Fenzl et al., 2014). Increases in energy intake post-exercise additionally appear to take place regardless of whether the individual is dieting or not (Thomas et al., 2012), and are often directed towards foods that are sweet and high in fat (Finlayson et al., 2009). Individuals who are not normally active may therefore be particularly vulnerable to a 'licencing' effect of participation in physical activity on energy intake, as they are more likely to experience exercise as a cognitive and physical challenge (Carlier & Delevoye-Turrell, 2017; Mullen & Hall, 2015).

To mitigate the above challenges to healthy participation in physical activity, there has been a recent shift in the way physical activity is promoted. The importance of positive affect is already gaining traction in public health messaging around physical activity (de Souto Barreto, 2013) and the design of physical activity initiatives (Foster et al., 2018; Gray et al., 2013). In comparison to prescribing structured physical activity, giving individuals access to physical activity opportunities that empowers them to experience positive affect has been associated with increased uptake and adherence to physical activity programmes (Allender et al., 2006; Dunton et al., 2018; Teixeira et al., 2012) and confidence to be regularly active (Lewis et al., 2016). Additionally, framing a walk as 'fun' or empowering adults to choose how they want to be active, has been found to have a positive influence on the amount and types of food people eat after the activity (Beer et al., 2017; Werle et al., 2015). Therefore, increasing positive affect during physical activity such that physical activity is not experienced as an 'effortful task' can bring dual benefits; promoting participation in physical activity, and reducing vulnerability to subsequent overeating.

An emerging approach to inducing positive affect during physical activity entails the use of virtual reality (VR) technology to gamify a workout (Mouatt et al., 2020). VR is an immersive experience whereby a headset and hand controllers enable users to interact with a computer-generated three-dimensional world incorporating visual, auditory, and other sensory information. VR exergames are experiences where interaction with a computer-generated environment requires physical activity from the user. Much like PlayStation and Wii exergames, VR exergames stem from the gaming industry and are specifically designed to maximise engagement while encouraging movement. By immersing the user in a digitally created environment, VR provides a step-change in the experience of physical activity to the extent that VR exergames can elicit higher power output without compromising exercise enjoyment (Farrow et al., 2019). They increase experienced arousal and positive affect, well beyond levels observed when exercise sessions are paired with television viewing (Bird et al., 2019; Zeng et al., 2017).

The use of virtual reality technology to elicit physical activity has received increased interest from researchers and decision-makers to promote physical activity and inform population nutrition interventions (Gao et al., 2020; Hoenink et al., 2020; Johnsen et al., 2014; Polechoński et al., 2020). To the authors' knowledge, this is the first study to evaluate the value of fully immersive VR exergaming to influence post-exercise eating behaviour. Specifically, we aimed to examine whether manipulating an individual's affective response to exercise via the use of VR can reduce post exercise: a) appetite, b) preference for foods that are sweet and high in energy density, and c) overall food intake (kcal). To enable us to draw stronger conclusions about the effects of altering affective response on eating behaviour, we guided participants through two sessions of the same cycling activity (when cycling was elicited by the VR exergame and when participants did not have access to VR), matching the sessions in duration, intensity, and energy expenditure.

2. Material and methods

2.1. Study design and setting

In a randomised cross-over study (See Supplemental File 1 for details), participants attended the Bristol VR Lab on three separate occasions; the first to become familiar with VR exergaming, followed by the two assessment cycling sessions. One of the sessions integrated VR exergaming (experimental), and one did not include VR (control). The exercise sessions were completed one week apart, at approximately the same time of the day (±1 h). The order of allocation to each assessment session was randomised using a random number generator. Given the nature of the experimental manipulation, we were unable to conceal this allocation from researchers or participants.

The University of Bristol Faculty of Science Ethics Committee approved the study (ref: 67101), which was conducted in accordance with the guidelines provided by the Declaration of Helsinki. All participants provided written informed consent.

2.2. Participants

Adult participants were recruited between September 2018 and January 2019. Based on the effect size of previous research into the impact of improving the exercise experience on self-serving of dessert and drink after exercise ($d = 0.05$; Werle et al., 2015), we estimated (using G*Power3.1.9.4) that 31 participants would enable detection of a similar effect with a two-tailed test, an α of 0.05, and adequate 80% power (Erdfelder et al., 1996). Participants were recruited if they were 18–65 years of age, willing to complete 15–25 min of static cycling and were not on a diet (self-reported). They were excluded if they; a) engaged in more than 150 min of moderate-to-vigorous physical activity (MVPA) per week, b) weighed more than 118 kg or were taller than 185 cm (due to equipment health and safety regulations), c) had a history of cardiovascular, respiratory, or endocrine system disorders, d) had a psychiatric disorder, e) had an injury or surgery on a leg or their back in the past two months, f) were on a restrictive diet, g) had a history of an eating disorder, h) smoked more than 5 cigarettes per day, i) were vegan or vegetarian, or j) had a food allergy or intolerance. The study flow chart is presented in Supplemental File 1. Initially 40 participants were recruited. However, three withdrew for personal reasons (1 female and 2 males) and 3 (male) were excluded because they met World Health Organisation recommendations for physical activity. Of the remaining 34 participants, 27 were female.

2.3. Material

VirZoom VR exercise bicycle. The VirZoom exercise bike is a lightweight (17.9 kg, 61x61 × 114.3 cm) stationary exercise bicycle. It is equipped with integrated sensors that are synchronised with a computer that is paired with a VR headset. In combination, this enables exercise to be performed while immersed in VR. We selected the VirZoom Arcade, a series of simulation minigames (details in Supplemental File 2) with which the player engages by pedalling and by leaning on either side. Resistance (ranging from 1 to 6) was kept constant across conditions and a researcher (SS) continuously monitored sessions. Each exercise session started and ended with a short period of warm up/restoration cycling, with low pedalling resistance. The same VR game was used for the warm up and restoration (kayak), but participants pre-selected the game they wanted to play in the main exercise session after testing all games in an earlier familiarisation session. Pedalling resistance was increased during the rest of cycling to facilitate MVPA.

Virtual Reality Equipment. The VirZoom bicycle was paired to a computer and an HTC Vive PRO Headset via a Bluetooth connection. The headset was also linked to a secondary SAMSUNG screen to replicate what participants saw in VR. Motion sensors were located on the left and behind participants to detect changes in body positioning. Noise transmitted via the headset was adjusted to participants' preference, and all participants wore a VR-specific hygiene mask while cycling with VR.

2.4. Measures

2.4.1. General

The *Preference for and Tolerance of the Intensity of Exercise Questionnaire* (PRETIE-Q; (Ekkekakis et al., 2005)) evaluates how much a person tolerates and prefers intense exercise perceived as uncomfortable, which is known to impact how an individual experiences exercise (Ekkekakis et al., 2005). Separate 'tolerance' and 'preference' scales are issued on a 5-point Likert scale (1 = "I totally disagree" and 5 = "I totally agree") with 4-month test-retest reliability of 0.72 and 0.80 respectively (Ekkekakis et al., 2005).

General health was examined using the Medical Outcomes Study Short-Form- 36 Health Survey (SF-36; (Eisen et al., 1980)). Eight domains of health status are evaluated (physical functioning, physical role limitations, bodily pain, general health perceptions, energy/vitality, social functioning, emotional role limitations, and mental health) and scores for each scale range from 0 (worst possible health) to 100 (best possible health). Using data from the British Omnibus National Survey (Bowling et al., 1999), Cronbach's alpha coefficients for the eight scales range from 0.73 to 0.96 (Burholt & Nash, 2011).

Disinhibited eating is a behavioural domain of eating associated with an increased vulnerability to external food cues and consumption of high calorie foods (Cornelis et al., 2014; De Lauzon et al., 2004). It was measured using the Uncontrolled Eating Scale of the Three-Factor Eating Questionnaire (TFEQ_18; Karlsson et al., 2000), scored on a Likert scale (1–4). The TFEQ-18 has been shown to have good factor structure (Cronbach's coefficient $\alpha = 0.78–0.94$) and is widely used in studies of eating behaviour (e.g. De Lauzon et al., 2004).

2.4.2. Psychological response to exercise

In line with general recommendations for exercise programme design (Haile et al., 2015), several measures were used to capture the various domains of an individual's response to exercise.

Exercise enjoyment was measured using the Physical Activity Enjoyment Scale (PACES; (Kendzierski & DeCarlo, 1991)), an 18-item questionnaire that is completed (on a 7-point bipolar Likert scale) as soon as the session had finished and participants stepped off the static bike. The reported Chronbach's alpha is 0.96 (Motl et al., 2001) and the scale has been found to be reliable in adults (Graves et al., 2010; Mullen et al., 2011).

Affect while exercising was examined using verbal self-reported ratings on a) The Feeling Scale (Hardy & Rejeski, 1989), which measures affective valence on an 11-point bipolar scale ranging from −5 (displeasure) to 5 (pleasure); b) The Felt Arousal Scale (Ekkekakis et al., 2011), which evaluates the subjective experience of arousal (i.e. perceived activation) on a bipolar scale from 1 (low arousal) to 6 (high arousal). These scales are often used separately (e.g. Bird et al., 2020) or in unison to track the affective response to exercise as a circumplex model (e.g. Buscombe & Inskip, 2013; Ekkekakis et al., 2011; Qin et al., 2017) that places an individual in one of four quadrants: 1) high arousal pleasant affect (i.e. energy, vigour); 2) high arousal unpleasant affect (i.e. distress, tension); 3) low arousal pleasant affect (i.e. calm, relaxed); 4) low arousal unpleasant affect (i.e. fatigue, boredom). The scales were administered verbally by the researcher at the end of a warm-up phase, every 10 min until the start of the cool-down phase, and upon finishing the exercise session.

Perceived exertion during exercise was measured using the Borg's Ratings of Perceived Exertion (RPE) Scale (Borg, 1998). The scale comprises a numerical list corresponding to a series of descriptors regarding the levels of exertion that range from 6 ("no exertion at all") to 20 ("maximal exertion"). Since responses on this scale are closely related to heart rate, the scale is used widely in the field of sports medicine (Williams, 2017). The scale was administered with the same frequency schedule as the measures of affect.

2.4.3. Physiological response to exercise

Heart rate and energy expenditure were monitored throughout the exercise sessions using a Fitbit Charge 2 (©Fitbit, Inc, San Francisco, CA), a physical activity monitor that features a tri-axial accelerometer and collects real-time data, including heart rate and energy expenditure. Prior to each exercise session, the Fitbit was synchronised to the participant's weight, height, age, and sex. Heart rate was measured alongside measures of affect and perceived exertion. The Fitbit Charge has been shown to provide adequate estimates of heart rate when compared to ambulatory electrocardiogram; mean absolute percent error (MAPE) inferior to the recommended 10% criterion for both walking and running (Nelson & Allen, 2019). Meta-analysis shows that it does not significantly deviate from criterion measures when measuring energy expenditure derived from cycling (O'Driscoll et al., 2020).

2.4.4. Appetite and eating behaviour

Appetite was evaluated by combining self-reported sensations of hunger and fullness, as measured by linear 100 mm Visual-Analogue Scales (VAS) ranging from 'Not at all' to 'Extremely' completed in paper and pencil. A composite appetite score was derived from these measures using an approach recommended by Rogers & Hardman (Rogers & Hardman, 2015): (Hunger + (100-Fullness))/2. VASs are commonly used in appetite research (Beer et al., 2017). A 100 mm paper and pen VAS scale was also used to measure self-reported sensations of nausea.

Food preferences were evaluated via a computerised 2-alternative forced-choice task developed at the Nutrition and Behaviour Unit, of the University of Bristol. Images of 18 foods were carefully selected to assess how preference is governed by energy density and by taste (sweet/savoury). A description of the foods is provided in Supplemental File 3, along with their nutritional information. In a series of trials ($N = 153$), an exhaustive combination of every food pair was presented (side-by-side). Participants were asked to "Imagine you can have one of these foods to eat right now. Which one would you choose? Only these portions are available", and participants selected the food on the left or the right by pressing the left or right arrow keys on a keyboard. The order of the trials was randomised. Assessment of food preferences focussed on frequency of selecting foods classified as high energy dense according to the British Nutrition Foundation (i.e., > 4 kcal/g; 3 out of 18 foods presented; (British Nutrition Foundation, 2021)) or sweet foods (6 out of 18 foods presented). This computerised task has been used previously to measure valuation of protein foods (Buckley et al., 2019) and has been shown to reflect self-serving behaviour and food intake (Cox et al., 2021).

Food intake was calculated from an *ad libitum* buffet meal provided to participants (see Supplemental File 3 for details) after each cycling session, once participants had completed PACES, VAS and the food preferences computerised task. The meals were consumed alone and devoid of external distractions until the participant notified the researcher of meal completion. Participants were instructed to eat until they felt “comfortably full” and to inform the researcher when they had finished eating. All participants completed their meals within 30 minutes. Food intake (kcals) was calculated by weighing the food before and after consumption. A measure of total calories was then derived by converting weights into calories using information on food packaging.

2.5. Procedure

Participants were told that the objective of the study was to assess whether VR should be introduced in gyms. Participants were instructed to avoid eating or drinking anything apart from water for at least 3 h before each visit to the Bristol VR Lab, and that the objective was to minimise nausea or stomach discomfort during exercise. They were also told that to comply with university health and safety regulations, a meal would be provided at the end of each session. Meal duration was monitored by the researcher.

Familiarisation session. To ensure inactive adults were recruited, participants were asked to describe their physical activity habits, particularly in the previous month, and were queried on the type, duration, frequency, and intensity of the physical activity. Participants were introduced to VR using a general information sheet (see Supplemental File 4). The PRETIE-Q and SF-36 were administered, height and weight were measured, and participants were asked about their physical activity habits. They were then given written guidelines on how they should respond to the verbal assessment of affect and perceived exertion during exercise. Participants were then guided through an initial exposure to exercise in VR, and the researcher requested several verbal ratings of affect and perceived exertion during the exercise session. Finally, participants completed the PACES, and they were given the *ad libitum* meal.

Assessment sessions. See Fig. 1 for exact timings. The assessment sessions differed solely on whether participants exercised with VR or without VR. Participants were asked the time when they last ate, they were weighed, were given a Fitbit to wear on their non-dominant wrist, completed the self-reported VAS, and then the food preference task. The Fitbit was then set on “spinning” mode to record energy expenditure. After a 5-min warm-up, the pedalling resistance was increased, and the researcher monitored heart rate to support participants achieve a heart rate within 65% and 85% of age-determined maximum heart rate. Monitoring of heart rate ensured participants exercised within the heart rate thresholds defining moderate-intensity physical activity (Physical Activity Guidelines Advisory Committee, 2008). When heart rate deviated outside the bounds, the researcher instructed the participant to increase or decrease pedalling speed. When participants had expended 110 kcal, pedalling resistance was reduced, and participants were instructed to pedal slowly. The exercise session ended when participants had expended approximately 120 kcal, as in previous work (McCaig et al., 2016). Verbal ratings of affect and perceived exertion were taken every 5 min. Participants then completed the food preference task, VAS and PACES, and were given the *ad libitum* meal. Prior to debrief, participants were asked to describe the purpose of the study.

2.6. Statistical analysis

The study, hypotheses and data analysis plans were pre-registered on the Open Science Framework (https://osf.io/na9zh). Two-tailed statistical analyses were conducted using SPSS v24.0 (SPSS Inc.: Chicago). Statistical significance was assumed at $p < 0.05$. For estimates of effect size, Cohen’s $|d|$ was used for data containing one factor and partial η^2 was used for ANOVA. For the former, we used the guide provided by Cohen ((Cohen, 1988); small = 0.2, medium = 0.5, large = 0.8) and for the latter we used values from Miles and Shevlin ((Miles & Shevlin, 2001), small = 0.01, medium = 0.06, large = 0.14). Descriptive data were summarised using means and standard deviations. To maintain consistency, means and standard deviations were also calculated in cases where nonparametric tests were carried out.

Two-way (order of allocation x condition) mixed ANOVAs were carried out to examine the impact of integrating VR exergaming on exercise enjoyment, exercise duration, and exercise-related energy expenditure, as well as mean scores in activation, pleasantness, perceived exertion, and heart rate. The circumplex model of affect was used to depict changes in affect during exercise across conditions (Qin et al., 2017). The associated output is generated from ratings on the Felt Arousal Scale and the Feelings Scale.

Unless assumptions were violated, paired-samples *t*-tests were used to examine whether participants arrived at each test session having restrained from eating for a similar amount of time prior to testing, and the volume of water consumed during exercise. Pre-vs post-exercise changes in appetite, nausea, and thirst were compared between conditions using a two-way (time x condition) repeated-measures ANOVA.

To evaluate the impact of exercise in VR on food preferences, data

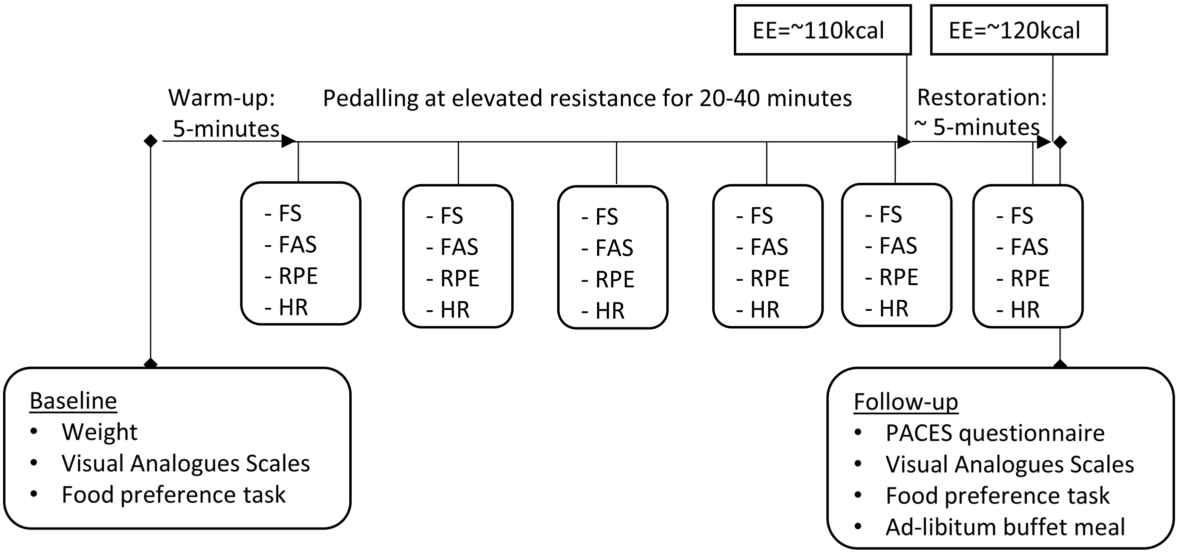

Fig. 1. Structure of the assessment cycling sessions. FS: Feeling Scale; FAS: Felt Arousal Scale; RPE: Rating of Perceived Exertion; MVPA: Moderate-to-vigorous physical activity; EE: Energy Expenditure; PACES: Physical Activity Enjoyment Scale.

gathered from the computerised food-preference task were extracted using R software (R Development Core Team., 2010). For each participant, condition and time point (pre/post exercise) we computed the number of occasions that a selected food was classified as sweet (maximum possible = 48) or energy dense (maximum possible = 87). Using these frequencies, we then used two-way (time x condition) repeated-measures ANOVAS to assess the effect of condition on exercise-induced changes in food choice. To examine the effects of exercise with VR on energy intake, information on the calories consumed in the post-exercise buffet meal were calculated. A two-way mixed ANOVA (order of allocation x condition) was conducted to examine the impact of exercise in VR on food intake. Given the link between a disinhibited eating style and vulnerability to overeating, scores on the Uncontrolled Eating scale of the TEFQ-18 were tested as a covariate. The Bonferroni correction was applied for multiple comparisons.

3. Results

3.1. Participant characteristics

Participant characteristics are displayed in Table 1. Scores relating to scale PRETIE-Q were in the 40th percentile when compared to normative data from U.S. college women (Ekkekakis et al., 2008). Respectively, mean scores from the SF-36 and the TFEQ-18 Uncontrolled Eating Scale were within one standard deviation of scores reported by the British National Office of Statistics (see Burholt & Nash, 2011) and those observed in the general population (see De Lauzon et al., 2004). At debrief, participants were asked to summarise the aims of the study and describe the researchers' hypotheses. None of the participants were able to guess the true objective of the study.

3.2. Affective response to exercise with VR

Table 2 presents the effects of integrating VR exergaming during exercise. Two-way mixed ANOVAs revealed that although exercise enjoyment, pleasure, and arousal were significantly higher in the VR condition than in the control condition (all $p < 0.01$), there were no differences in perceived exertion, heart rate, energy expenditure, and duration of the exercise sessions. Minimum heart rate as a percentage of maximum heart rate during the exercise session was similar across conditions (VR: 52 ± 14%, C: 56 ± 11%; SED = 2.7%; $F(1, 32) = 2.5$, $p = 0.12$, $\eta^2 p = 0.07$), while the heart rate range as a percentage of maximum heart rate was moderately greater when participants cycled in VR (19 ± 14%) compared to the control exercise session (12 ± 11%; SED = 2.6%; $F(1,32) = 7.4$, $p < 0.05$, $\eta^2 p = 0.19$). Two-way mixed ANOVAs further revealed a study order and condition interaction on mean heart rate ($F(1,32 = 7.3$, $p < 0.05$, $\eta^2 p = 0.2$). Bonferroni adjusted pairwise comparisons indicated that study order only affected the control condition, whereby mean heart rate when cycling without VR (control) was elevated if they had already completed the VR condition (112.3 ± 8.9 bmp) compared to participants for whom this was the first exercise session (103.1 ± 8.9 bmp; $p < 0.05$). Study order did not affect mean heart rate in the VR condition or other measures of affective response to exercise (all $p > 0.05$).

Table 1
Participant characteristics (n = 34, 27 (79%) female).

	Mean ± SD (range)
Age (years)	23.5 ± 3.5 (20.0–33.0)
Body Mass Index (kg/m^2)	22.5 ± 3.5 (18.6–29.7)
PRETIE-Q	
Tolerance of high intensity exercise	21.1 ± 4.5 (12.0–30.0)
Preference of high intensity exercise	22.7 ± 5.9 (12.0–34.0)
Short Form-36 (0–100)	
Role limitations (physical health)	94.7 ± 16.2 (25.0–100.0)
Role limitations (emotional health)	75.8 ± 33.6 (0–100.0)
Energy/Vitality	56.7 ± 12.7 (30.0–75.0)
Mental health	75.1 ± 14.4 (44.0–96.0)
Social functioning	89.1 ± 17.9 (37.5–100.0)
Bodily pain	87.9 ± 11.4 (67.5–100.0)
General Health	65.8 ± 14.4 (30.0–95.0)
Physical functioning	94.4 ± 5.6 (85.0–100.0)
TFEQ-18 uncontrolled eating scale	19.6 ± 3.7 (12.0–26.0)

Table 2
Physical activity enjoyment and physiological demand of exercise sessions (n = 34). *p < 0.05. VR: Virtual reality, SD: Standard deviation, SED: Standard error of difference.

	Control	VR	SED	F (df = 1,32)	p	η^2p
	Mean ± SD	Mean ± SD				
Physical activity enjoyment (PACES; scores: 18–126)	61.1 ± 17.6	96.5 ± 17.3	4.9	51.8	<0.001*	0.62
Pleasure (Feeling Scale; scores: 5 - +5)	1.6 ± 1.6	3.0 ± 1.3	0.3	27.9	<0.001*	0.47
Activation (Felt Arousal Scale; scores: 1–6)	2.2 ± 0.8	3.3 ± 1.0	0.2	38.5	<0.001*	0.55
Rating of perceived exertion (scores: 6–20)	11.5 ± 2.9	11.9 ± 2.5	0.7	0.22	0.64	0.0
Heart Rate (bpm/min)	108.0 ± 13.2	105.8 ± 15.0	3.0	0.33	0.57	0.01
Duration (min)	38.2 ± 8.0	37.9 ± 9.0	1.8	0.02	0.89	0.00
Kcal expended	138.4 ± 33.0	133.1 ± 26.4	4.1	1.6	0.22	0.05

The circumplex model (Fig. 2) depicts pooled affect change during exercise with and without VR. Regardless of exercise condition, participants started their exercise in the "low activation, pleasure" dimension. In the control condition affect remained in this dimension throughout. However, in the VR condition it transitioned to "high activation, pleasure" within 10 min, and affect remained in that dimension for 20 min, after which it returned to dip back into the "low activation, pleasure" dimension.

3.3. Effects of VR exergaming on appetite and food choice

Wilcoxon signed rank tests indicated similar amounts of water were consumed during exercise in the VR (361 ± 278 ml) and control conditions (329 ± 168 ml; SED = 46.2 ml; $Z = -0.27$, $p = 0.79$, $d = 0.05$), as was the length of time participants had not eaten before starting exercise (VR: 471 ± 280 min; control: 481 ± 298 min; SED = 56 min; $Z = -0.78$, $p = 0.44$, $d = 0.14$). Two-way repeated measures ANOVA revealed a moderate main effect of exercise condition on reported nausea in the VAS scales (SED = 1.9 mm; $F(1,33) = 4.4$, $p < 0.05$, $\eta^2 p = 0.12$). The use of VR resulted in participants reporting elevated sensations of nausea after the exercise session compared to baseline (5 ± 8 mm to 14 ± 22 mm on the Nausea VAS scale); exercise without VR did not impact sensations of nausea (6 ± 10 mm to 5. ± 8 mm; $F(1,33) = 10.1$, $p < 0.05$, $\eta^2 p = 0.23$). For four participants, scoring on the VAS shifted by at least 40 mm in the VR condition. We proceeded in controlling for nausea in subsequent analyses, as removal of the four cases provided similar results (Supplemental File 5).

Hunger ratings at baseline were similar across exercise conditions (VR: 59 ± 22 mm, control: 58 ± 21 mm; SED = 58 mm; $Z = -0.18$, $p = 0.85$; $d = 0.03$), as was the time since last eaten (all more than 180 min; VR: 471 ± 280 min, control: 481 ± 298 min; SED = 56 min; $Z = -0.77$, $p = 0.43$; $d = 0.13$). Appetite was found to increase with exercise (mean changes in VAS scoring from baseline to after exercise: VR = 4 mm and control = 9 mm, SED = 2.7 mm; $F(1,32) = 8.3$, $p < 0.01$; $\eta^2 p = 0.20$), but exercise condition did not have a significant effect on this change

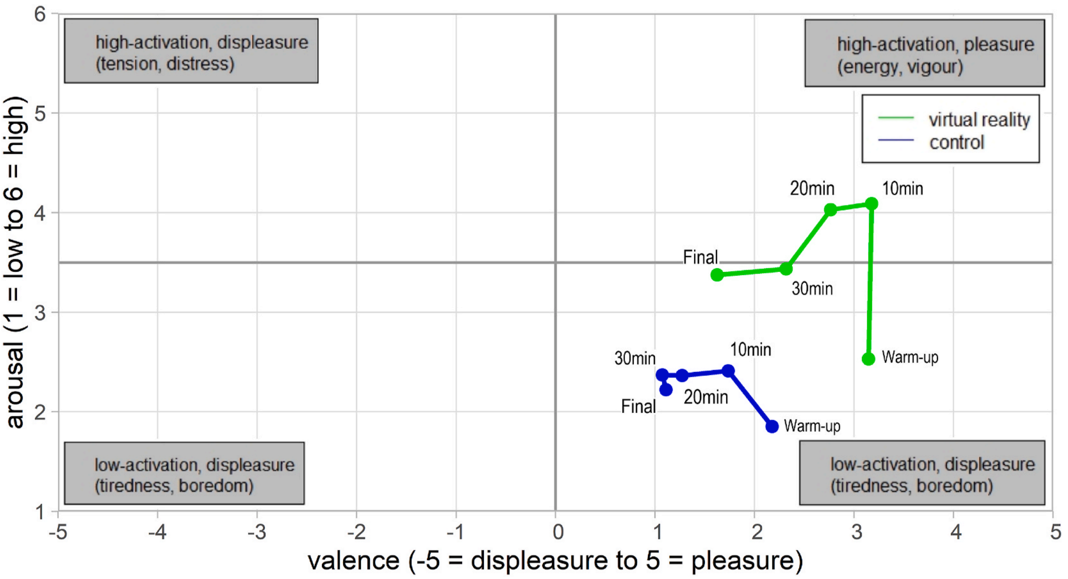

Fig. 2. Affect Circumplex Model (Schlosberg, 1952). Activation measured via the Felt Arousal Scale and pleasure measured via the Feeling Scale.

(interaction term, F(1,32) = 1.2, p = 0.68; η^2p = 0.01). In the food-preference task, the frequency with which participants selected foods of high energy density over alternatives at baseline was the same for the two conditions (VR: 19 ± 6.7 times, C: 19 ± 5 times; SED = 0.84 times; t (33) = - 2.8, p = 0.78; d = 0.28), as was the frequency with which they selected sweet over savoury foods (VR: 43 ± 13 times, C: 43 ± 16 times; SED = 1.8 times; t (33) = 0.08, p = 0.90; d = 0.08). The pre-post*exercise condition interactions failed to reach statistical significance in preference for high energy dense foods (F (1,32) = 1.9; p = 0.18; η^2p = 0.06) as well as sweet foods (F (1,31) = 0.04; p = 0.84; η^2p = 0.01). Study order did not alter results (all p > 0.05).

3.4. *Effects of exercise with VR on energy intake*

Participants were given their meal approximately 6 min (±2 min) after exercise completion. Participants ate 12% (106 kcal) less after the exercising in VR compared to control, with a large effect size (VR: 809 ± 437 kcal; control:915 ± 498 kcal; SED = 42.3 kcal; F (1, 31) = 7.8; p = < 0.01; η^2p = 0.20). Individual differences in disinhibition did not have a main effect on food intake (F(1,30) = 0.8; p = 0.78; η^2p = 0.01), nor did it influence the effect of exercise condition (interaction: F (1, 30) = 0.6; p = 0.43; η^2p = 0.20). However, Fig. 3 demonstrates that there were large inter-individual differences in effects of VR exergaming on food intake. These could not be attributed to weight, as participants' weight did not change in the inter-condition interval (SED = 0.4 kg, t(33) =

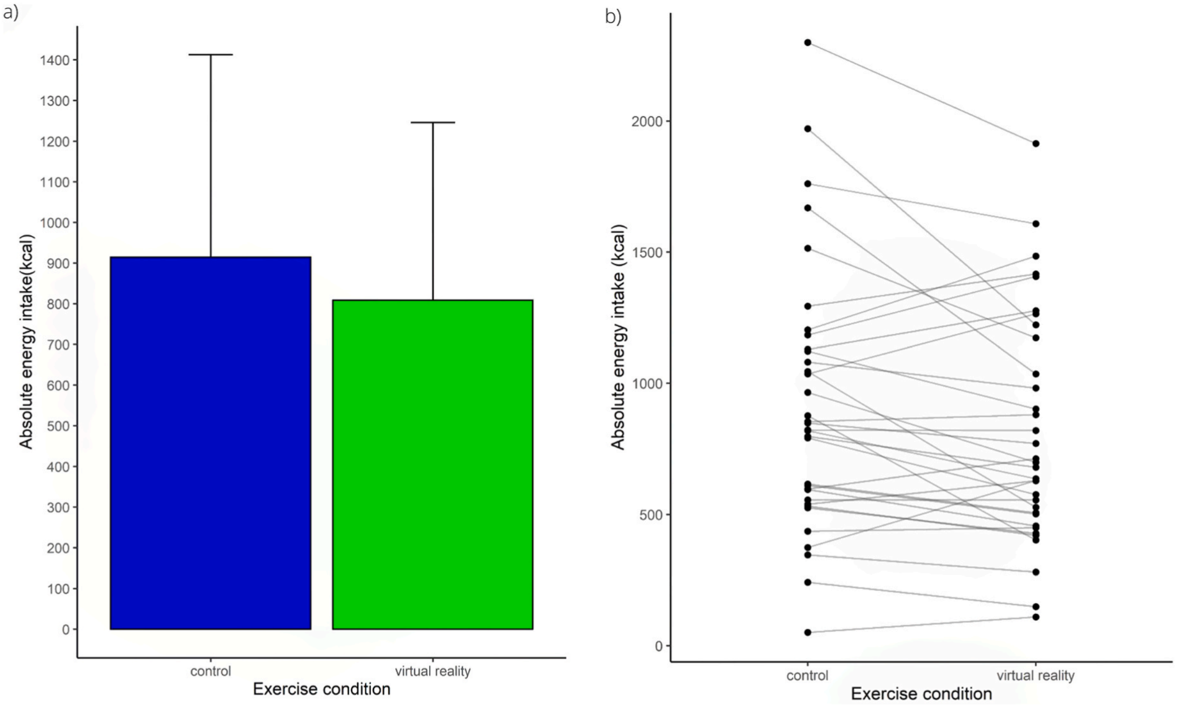

Fig. 3. Absolute food intake in response to cycling while engaged in a VR exergame compared to control in terms of a: a) Mean (with standard deviation); b) individual responses.

0.20, $p = 0.84$; $d = 0.04$).

In a post-hoc analysis we additionally evaluated relative energy intake, following the methodology utilised in previous research: absolute energy intake – exercise-induced energy expenditure (e.g. Rocha et al., 2018). A two-way repeated ANOVA revealed relative energy intake to be lower after VR exergaming (676 ± 433 kcal) compared to the control exercise (776 ± 497 kcal; SED = 42 kcal; $F(1,31) = 7.8$, $p < 0.01$; $\eta^2p = 0.20$). Order of study allocation did alter the effect of exercise condition ($F(1,31) = 0.09$, $p = 0.77$; $\eta^2p = 0$).

4. Discussion

This study set out to explore the potential of VR exergaming to modulate the interplay between a bout of physical activity and subsequent eating behaviour. When VR exergaming was incorporated into a 30-min static cycling session, inactive adults reported greater exercise enjoyment compared to an otherwise identical cycling session, without VR. The workout with VR generated "high arousal and pleasure". Further, VR exergaming resulted in a 12% reduction in post-exercise food intake, albeit individual differences were observed. Together, our results demonstrate that affect plays an important role in the relationship between physical activity and subsequent food consumption.

The observed effects of VR exergaming on energy intake are consistent with earlier research that has used alternative means to improve participants' affective response to physical activity (Beer et al., 2017; Werle et al., 2015). Within the context of daily energy intake, a mean reduction of 106 kcal in food consumption is small. However, given that mean energy expenditure from the cycling session was 130 kcal, the difference in post-exercise food intake found in this study is clinically meaningful for someone engaging in regular physical activity to achieve or maintain a healthy weight (Hall et al., 2011).

Findings additionally reinforce the evidence against biologically driven post-exercise compensatory energy intake (Dimmock et al., 2015; Rocha et al., 2015, 2018). In this study, there were no differences between conditions in the muscles activated (both entailed cycling), or mean intensity, duration, energy expenditure, and self-reported exertion from the activity. Yet, the incorporation of VR was sufficient to alter energy intake, particularly among those individuals who displayed high post-exercise food intake in the control condition. Findings thus parallel previous research showing increases in food intake in anticipation of exercise do not reflect compensation for actual energy expenditure (Barutcu et al., 2020, 2021), rather individual differences in response to exercise labelling (Fenzl et al., 2014), and increased vulnerability to eat when anticipating exercise among restrained eaters (Sim et al., 2018). Collectively, evidence favours the existence of a 'licencing' phenomenon in the interface between physical activity and eating behaviour, which could in part be mitigated by altering how the individual experiences physical activity.

Building on the strength model of self-control (Baumeister et al., 2016) and the self-determination theory of eating regulation (Verstuyf et al., 2012), exertion of cognitive effort to complete a prescribed workout results in a depletion of cognitive resources required to exert control over other health-related behaviours, such as indulging in pleasurable but unhealthy foods (Dimmock et al., 2015). By using VR to generate a positive affective response to physical activity, some participants in this study may have found the cycling activity as less resource-demanding and more satisfying and were therefore less likely to seek a food reward. Food intake in this study could not be attributed to increased hunger, as self-reported appetite was similar across conditions.

There are several ways VR might be hypothesised to influence the affective response to exercise. First, the VR exergames used in this study were commercially available adaptations of existing videogames, specifically designed to accentuate reinforcement and activation (Lorenz et al., 2015). Alike previous work (Bird et al., 2020; Zeng et al., 2017), VR exergaming in this study was found to increase arousal, positive valence, and enjoyment. The use of VR might have thus enabled inactive adults to experience reward during exercise, as normally reported by habitually active adults (e.g. Cheval et al., 2018). However, whether this is sufficient to generate the observed effect on food intake is unclear, given that as far as the authors are aware there are no studies like this one in active adults and the literature around post-exercise energy intake in active adults is still unclear (Melanson et al., 2013). It may also be possible to speculate that VR exergaming increased participants' experienced self-efficacy, which has been linked to adherence to goal-oriented behaviours (Room et al., 2017). The VR exergames adjusted to participants' cycling performance and provided in-game rewards to increased cycling speed and real-time feedback; gaming characteristics that have been linked to increased perceived self-efficacy (Dos Santos et al., 2016; Lyons & Hatkevich, 2013; Zeng et al., 2017). An alternative hypothesis relates to accumulating evidence for a more overarching analgesic effect of immersive VR technology (Matamala-Gomez et al., 2019), which has been shown to inhibit fatigue, tension and depression when combined with exercise (Qian et al., 2020) and to enable high-intensity exercise to be achieved without altering enjoyment (Farrow et al., 2019). Although understanding the mechanisms underpinning the effects of VR exergaming on food intake are beyond the scope of this paper, future research would benefit by incorporating VR rest and non-VR exercise control conditions and embed additional neurocognitive and physiological measures. The inclusion of non-exercise control arms would also enable the evaluation of the added value of VR exergaming on facilitating a negative energy balance.

It is noteworthy that most participants in this study were female, and we did not control for menstrual cycle or use of oral contraceptives. Evidence shows food intake is elevated in the luteal phase compared to the follicular phase of the cycle (Dye & Blundell, 1997), with change in food intake across the cycle being greater than that observed between conditions in this study (Asarian & Geary, 2013). There is also some evidence that the use of oral contraceptives may moderate the effect of physical activity on subsequent food intake (Rocha et al., 2015, 2018), although previous research into the manipulation of the affective response to exercise has not accounted for menstrual cycle (e.g. Beer et al., 2017; Werle et al., 2015). By adopting a randomised crossover design, we have reduced the likelihood that menstrual cycle phase of female participants co-varied systematically with order of allocation to condition, and we did not find differences between conditions in baseline hunger ratings nor preference for specific food items. A recent study did not find differences in post-cycling session appetite markers, subjective appetite scores or three-day average total energy intake when female participants exercised in the early follicular phase compared to the mid luteal phase (Kamemoto et al., 2022). However, caution is recommended when drawing conclusions from these findings, as the authors did not include a non-exercise control arm and compared post-exercise food intake at the early follicular phase to food intake at the mid luteal phase. Previous work shows that food intake is relatively similar at these phases of the menstrual cycle, but lower in the mid follicular and the periovulatory phases (Asarian & Geary, 2013). A larger study, with the inclusion of more male participants, careful monitoring of menstrual cycle (enabling comparisons between the mid-to-late follicular or peri-ovulatory phases and luteal or early-follicular phases) and controlling for oral contraceptive use, would be better powered to explore intra- and inter-individual factors (e.g. sex, inhibitory control, tolerance of increased exercise intensity) that could have played a role in the highly variable eating response to VR exergaming.

There are additional limitations to this study that need to be considered. In efforts to conceal the true aim of the study, we did not monitor food choices made while eating, preventing comparison to earlier research that has found greater consumption of specifically hedonic foods when physical activity is experienced as less pleasant (Werle et al., 2015). Second, our protocol for evaluating physical activity participation focused on the month prior to the familiarisation session; we may have included individuals who are normally active but had not been so for the previous month. Further, this study evaluated the immediate impact of a bout of VR-enhanced physical activity; it remains to be determined whether effects on eating behaviour are preserved over longer periods. In doing so, it would additionally be possible to compare the relative effect of the affect manipulation in the context of the notable changes in food intake seen in women across their menstrual cycle (Asarian & Geary, 2013). More generally, further research is needed to establish whether chronic use of VR leads to a sustained improvement in the affective response to physical activity and the impact it may have on eating behaviour across time. Although the literature suggests that VR exergaming can elicit higher intensity physical activity (Farrow et al., 2019), this cannot be confirmed in the current study as participants did not sustain MVPA throughout the exercise sessions.

5. Conclusion and implications

A more detailed understanding of how VR exergaming can enhance the affective response to physical activity has appealing potential. Policy-making is increasingly recognising the importance of promoting positive physical activity experiences to improve population-wide uptake to physical activity opportunities (Ekkekakis, 2017; WHO, 2018), and there is growing recognition of the value of VR technology to support weight management (Johnsen et al., 2014; Mcclure & Schofield, 2020; Polechoński et al., 2020). The effect on post-exercise energy intake for some individuals is particularly relevant in the context of obesity and type 2 diabetes mellitus. Although regular physical activity robustly improves fitness, cardiovascular health and insulin sensitivity (Kohl et al., 2012), individuals living with obesity and/or type 2 diabetes are more likely to be inactive and need to exert tight control on their energy intake. VR exergaming could provide a dual benefit for these individuals: facilitate engagement in physical activity and mitigation of individual risk to 'licencing' effects after exercise. It would be valuable that future longitudinal studies incorporate measures of cost, to permit the assessment of whether VR exergaming could offer a cost-effective solution.

VR exergaming could also be particularly useful to promote physical activity and overall wellbeing in people living with disabilities and mental health difficulties. These individuals are up to 62% less likely to meet WHO physical activity recommendations compared to the general population (Ginis et al., 2021) and are at greater risk of obesity and diabetes (Ells et al., 2006). Given the surge of scientific research around VR for personalised physical rehabilitation (Laver et al., 2017) and the proliferation of VR exergames that can elicit a wide range of movements, VR exergaming could offer these individuals an appealing physical activity opportunity.

Authors contribution

SS and JB jointly developed the research question and designed the research study. SS was led data collection and analysis of the data. JB developed the computerised food preference task. SS and JB jointly interpreted results. SS drafted the manuscript, with substantial contributions from JB. Both authors approved the manuscript submission and are personally accountable for the contents of the manuscript.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethical statement

The University of Bristol Faculty of Science Ethics Committee approved the study (ref: 67101), which was conducted in accordance with the guidelines provided by the Declaration of Helsinki. All participants provided written informed consent.

Declaration of competing interest

The authors declare that they have no competing interests. There was no partnership or agreement with the VR equipment company during this study.

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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.2022.106058.

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