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

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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

Abstract

An individual's affective (*i.e.*, emotional) response to exercise may be key to tackling post-exercise overeating. 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 had little impact on perceived physical exertion ($p = 0.64$), perceived appetite ($p = 0.56$), and preference for energy dense ($p = 0.18$) or sweet/savoury foods ($p = 0.84$). However, it did result in a 12% reduction in post-exercise food intake (mean difference: 105.9kcal; $p < 0.05$; $\eta^2p = 0.20$). The integration of VR in a cycling workout improves the affective experience of physical activity for inactive adults and reduces subsequent food intake. Further research is needed to better understand the value of virtual reality technology as an adjunct tool to support weight management.

Keywords: physical activity, virtual reality, food intake, weight management, affect

59 **1. Introduction**

60 Health benefits of regular physical activity include improved muscular and cardiorespiratory
61 fitness, bone and functional health, insulin sensitivity, and healthy weight control (Kohl et al.,
62 2012). Given its importance for the prevention and treatment of noncommunicable diseases
63 such as obesity, the World Health Organisation (WHO) has developed a Global Action Plan to
64 reduce worldwide physical inactivity (“NCDs | Governance: Development of a draft global
65 action plan to promote physical activity,” 2018). In some countries, physical activity has been
66 promoted via the introduction of national policies and schemes, but uptake and long-term
67 adherence to these programmes is often poor (Biddle & Batterham, 2015; Pavey et al., 2012).

68
69 In relation to weight management programmes, a separate concern is that participation in
70 physical activity can result in overeating in some individuals (King et al., 2007; Werle et al.,
71 2015), which subsequently interferes with weight loss attempts (Cawley, 2011; Drenowatz,
72 2015; King et al., 2007). Eating behaviour after a bout of moderate physical activity,
73 however, does not appear to be underpinned by an automatic biological necessity to restore
74 energy balance (Hall et al., 2011; Melanson et al., 2013; Rogers & Brunstrom, 2016). Rather,
75 accruing evidence suggests that it is driven by the valuation of effort exerted to engage in
76 physical activity and the cognitive ‘licencing’ of increased energy intake as a form of
77 compensation (Martins et al., 2007; McCaig et al., 2016; Werle et al., 2011). In line with this
78 view, individuals who experience a negative affective response to physical activity (i.e. high
79 levels of distress, fatigue, low enjoyment, autonomy and perceived competence), seem to
80 be more vulnerable to overeating after exercise (Fenzl et al., 2014). This phenomenon can
81 take place regardless of whether the individual is dieting or not (Thomas et al., 2012), and it
82 is often directed towards foods that are sweet and high in fat (Finlayson et al., 2009).

83 To mitigate the above challenges to healthy participation in physical activity, there has been
84 a recent shift in the way physical activity is promoted. The importance of positive affect is
85 already gaining traction in public health messaging around physical activity (de Souto
86 Barreto, 2013) and the design of physical activity initiatives (Physical activity and family-
87 based obesity treatment: a review of expert recommendations on physical activity in youth,
88 2018; Gray et al., 2013). In comparison to prescribing structured physical activity, giving
89 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.

A novel 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 augment 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 augmented 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). This study aims to be the first 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 fat, 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 hour). 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 (Werle et al., 2015), we estimated (using G*Power3.1.9.4) that 33 participants would be needed detect the same effect ($d_z = 0.52$; (Cohen, 1988)) with a one-tailed test, an α of 0.05, and 90% power (Erdfelder et al., 1996). Participants were recruited if they were 18 to 65 years of age and willing to complete 15-25 min of static cycling. They were excluded if they; a) engaged in more than 150 minutes 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, 61x61x114.3 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. 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 ONS Omnibus Survey (A 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 after exercise on a 7-point bipolar Likert scale. 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).

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).

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.

2.4.4. Appetite and eating behaviour

Appetite was evaluated by combining self-reported sensations of hunger and fullness, as measured by linear Visual-Analogue Scales (VAS) ranging from 'Not at all' to 'Extremely'. A composite appetite score was derived from these measures using an approach recommended by Rogers & Hardman (Rogers & Hardman, 2015): $(\text{Hunger} + (100 - \text{Fullness}))/2$. VASs are commonly used in appetite research (Beer et al., 2017; Sepple & Read, 1989), alongside measures of nausea.

Food preferences were evaluated via a computerised 2-alternative forced-choice task. 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 they 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., > 4kcal/gram; 3 out of 18 foods presented; (British Nutrition Foundation, n.d.)) or sweet foods (6 out of 18 foods presented).

Food intake was calculated from an *ad libitum* buffet meal provided to participants (see Supplemental File 3 for details). 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 (kcal) 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 three hours 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. All meals were consumed alone, and meal duration was monitored by the researcher.

Familiarisation session. 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.

278
279 *Assessment sessions.* See Figure 1. The assessment sessions differed solely on whether
280 participants exercised with VR or without VR. Participants were asked the time when they
281 last ate, they were weighed, were given a Fitbit to wear on their non-dominant wrist,
282 completed the self-reported VAS, and then the food preference task. The Fitbit was then set
283 on “spinning” mode to record energy expenditure. After a 5-minute warm-up, the pedalling
284 resistance was increased, and the researcher monitored heart rate to ensure it remained
285 within 65% and 85% of age-determined maximum heart rate. Monitoring of heart rate
286 ensured participants exercised within the heart rate thresholds defining moderate-intensity
287 physical activity (Physical Activity Guidelines Advisory Committee, 2008). When heart rate
288 deviated outside the bounds, the researcher instructed the participant to increase or
289 decrease pedalling speed. When participants had expended 110 kcal, pedalling resistance
290 was reduced, and participants were instructed to pedal slowly. The exercise session ended
291 when participants had expended approximately 120 kcal, as in previous work (McCaig et al.,
292 2016). Verbal ratings of affect and perceived exertion were taken every five minutes.
293 Participants then completed the food preference task, VAS and PACES, and were given the
294 *ad libitum* meal. Prior to debrief, participants were asked to describe the purpose of the
295 study.

296 **2.6. Statistical analysis**

297 The study, hypotheses and data analysis plans were pre-registered on the Open Science
298 Framework (<https://osf.io/na9zh>). Statistical analysis was conducted using SPSS v24.0 (SPSS
299 Inc.: Chicago). Statistical significance was assumed at $p < .05$. For estimates of effect size,
300 Cohen’s $|d|$ was used for data containing one factor and partial η^2 was used for ANOVA. For
301 the former, we used the a guide provided by Cohen ((Cohen, 1988); small = 0.2, medium =
302 0.5, large = 0.8) and for the latter we used values from Miles and Shevlin ((Miles & Shevlin,
303 2001), small = 0.01, medium = 0.06, large = 0.14). Descriptive data were summarised using
304 means and standard deviations. To maintain consistency, means and standard deviations
305 were also calculated in cases where nonparametric tests were carried out.

306
307 Two-way (order of allocation x condition) mixed ANOVAs were carried out to examine the
308 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. 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 gathered from the computerised food-preference task were extracted using the R environment (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 entered as a covariate.

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, none of the participants correctly guessed the objectives of the study.

Across all analyses, order of exposure to exercise in VR impacted neither the exercise experience nor eating behaviour (all $p > .05$).

3.2. Affective response to exercise with VR

Table 2 presents the effects of integrating VR exergaming during exercise. Although exercise enjoyment, pleasure, and arousal were significantly higher in the VR condition than in the control condition (all $p < 0.01$), differences in perceived exertion, heart rate, energy expenditure, and duration of the exercise sessions were negligible.

The circumplex model (Figure 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 minutes, and affect remained in that dimension for 20 minutes, after which it returned to dip back into the “low activation, pleasure” dimension.

3.3. Effects of VR exergaming on appetite and food choice

There were no reliable differences between exercise conditions in the water consumed during assessment (VR: 361 ± 277 ml; control: 329 ± 168 ml; $Z = -0.27$, $p = 0.79$, $d = 0.05$), or the time since participants had last eaten (VR: 462.0 ± 265.3 min; control: 494.4 ± 292.7 min; $t = 0.52$, $p = 0.61$, $d = 0.09$). Relative to control, exercising in VR was found to increase nausea (mean difference in VAS nausea change score = 9.5 mm; $p < 0.05$; $\eta^2 p = 0.23$). Therefore, we controlled for nausea in subsequent analyses of appetite, food preference, and food intake.

Appetite was found to increase with exercise (mean changes, VR = 4.4 mm and control = 7.8 mm; $p < 0.01$; $\eta^2 p = 0.20$), but exercise condition did not have a significant impact on this change (interaction term, $p = 0.56$; $\eta^2 p = 0.01$).

In the food-preference task, the pre-post*exercise condition interactions failed to reach statistical significance in preference for high energy dense foods ($p = 0.18$; $\eta^2 p = 0.08$) as well as sweet foods ($p = 0.84$; $\eta^2 p = 0.01$).

3.4. Effects of exercise with VR on appetite and energy intake.

Participants ate 12% (105.9 kcal) less after the exercising in VR compared to control, with a large effect size (VR: 808.9 kcal $\pm$ 437.2; control: 914.8 kcal $\pm$ 497.9; $p < .05$; $\eta^2 p = 0.20$).

The independent effect of condition was significant after controlling for individual differences in disinhibition which, itself, was not a significant predictor of intake. ($p = 0.43$; $\eta^2 p = 0.02$).

4. Discussion

This study set out to be the first 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-minute 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. 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), and it adds to the literature demonstrating the value of VR technology to support weight management (Johnsen et al., 2014; McClure & Schofield, 2020; Polechoński et al., 2020). Within the context of daily energy intake, a mean reduction of 109kcal in food consumption is small. However, given that mean energy expenditure from the cycling session was 130kcal, 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).

These findings additionally reinforce the view that a tendency to overeat after participating in a bout of moderate physical activity is attributable to psycho-cognitive processes associated to the physical activity experience (Dimmock et al., 2015; Fenzl et al., 2014).

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. VR exergaming solely impacted participants’ affective experience. The design of

VR exergames and physical activity programmes should therefore focus on maximising the affective experience.

Previous research shows that individuals plan to eat more when anticipating aerobic physical activity later in the day (Barutcu et al., 2019), and they alter their food intake on the basis of how many calories they believe they have expended in a workout (McCaig et al., 2016). This suggests that individuals 'licence' elevated food consumption in response to assumptions of future or past energy expenditure (Barutcu et al., 2019). In this study, manipulating affect did not alter food choice prior to eating; participants were aware that they would be undertaking the same workout across conditions. Inducing positive affect however may have helped participants better regulate their energy intake when eating. 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, participants in this study may have found the cycling activity as less resource-demanding and more satisfying, and they were therefore less vulnerable to disinhibited eating. In support, differences in food intake in this study could not be attributed to increased hunger, as self-reported appetite was similar across conditions. Further research is warranted.

The present study has several strengths. Via the incorporation of VR exergaming, this is the first study to have manipulated affective response to physical activity while keeping all other parameters constant and comparing intra-individual changes in food intake. Further, it is the first to examine the impact of this manipulation on food consumption in adults identified as inactive. There are, however, some limitations 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 hedonic foods when physical activity is experienced as less pleasant (Werle et al., 2015). 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 long periods. 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.

5. Conclusion and implications

A more detailed understanding of how VR exergaming can enhance the affective response to physical activity and influence subsequent eating behaviour has appealing potential. VR exergaming modified food intake regardless of reported increases in appetite. Inactive adults are more likely to experience exercise as effortful and unpleasant (Parfitt et al., 2006), and have been found to be more vulnerable to overeating following physical activity (Beaulieu et al., 2018; Dorling et al., 2018; Shook et al., 2015). A tool that can help these individuals learn to enjoy physical activity and change their eating habits could be very valuable in weight management programmes.

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.

The COVID-19 pandemic has accelerated the acceptability of digital solutions to support health and social care (Golinelli et al., 2020), and the future role of VR in the health sector is increasingly more evident (PwC & Digital Catapult, 2019). This study provides preliminary evidence that VR exergaming can generate a positive physical activity experience for inactive adults without compromising the activity itself, and it can reduce subsequent food intake. Further research is needed to better assess its value as a targeted intervention for people vulnerable to overeating after physical activity, and to empower people to confidently participate in sports.

6. Acknowledgements

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7. 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.

8. Conflict of Interest

The authors declare that they have no competing interests.

9. Availability of data and materials

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

10. Figures

Figures uploaded separately. Captions below:

Figure 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.

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

11. Tables

	Mean ± SD (range)	
Age (years)	23.5 ± 3.5 (20.0-33.0)	493
Body Mass Index (kg/m ²)	22.6 ± 3.5 (18.6-29.7)	494
PRETIE-Q		495
Tolerance of high intensity exercise	21.1 ± 4.5 (12.0-30.0)	496
Preference of high intensity exercise	22.7 ± 5.9 (12.0-34.0)	497
Short Form-36 (0-100)		498
Role limitations (physical health)	94.7 ± 16.2 (25.0-100.0)	499
Role limitations (emotional health)	75.8 ± 33.6 (0-100.0)	500
Energy/Vitality	56.7 ± 12.7 (30.0-75.0)	501
Mental health	75.1 ± 14.4 (44.0-96.0)	502
Social functioning	89.1 ± 17.9 (37.5-100.0)	503
Bodily pain	87.9 ± 11.4 (67.5-100.0)	504
General Health	65.8 ± 14.4 (30.0-95.0)	505
Physical functioning	94.4 ± 5.6 (85.0-100.0)	506
TFEQ-18 uncontrolled eating scale	19.6 ± 3.7 (12.0-26.0)	

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

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			Control	VR	F	p	η^2p
			Mean $\pm$ SD	Mean $\pm$ SD	(df=1,32)		
Physical activity enjoyment (PACES; scores: 18-126)			61.1 $\pm$ 17.6	96.5 $\pm$ 17.3	51.8	<0.01	0.62
Pleasure (Feeling Scale; scores: -5 - +5)			1.6 $\pm$ 1.6	3.0 $\pm$ 1.3	27.9	<0.01	0.47
Activation (Felt Arousal Scale; scores: 1-6)			2.2 $\pm$ 0.8	3.3 $\pm$ 1.0	38.7	<0.01	0.55
Rating of perceived exertion (scores: 6-20)			11.5 $\pm$ 2.9	11.9 $\pm$ 2.6	0.22	0.64	0.01
Heart Rate (bpm/min)			108.0 $\pm$ 13.2	105.8 $\pm$ 15.0	0.33	0.57	0.01
Duration (min)			38.2 $\pm$ 8.0	37.9 $\pm$ 9.0	0.02	0.89	0.00
Kcal expended			138.4 $\pm$ 33.0	133.1 $\pm$ 26.4	1.6	0.22	0.05

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524 **Table 2** Physical activity enjoyment and physiological demand of exercise sessions (n=34)

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795 **13. Supplemental Files**

796 Supplemental File 1: Study flow chart (.docx).

797 Supplemental File 2: VR exergames offered to participants (.docx). The games are part of the
798 VirZoom Arcade, accessible directly via some VR headsets (e.g. Oculus Quest), a Playstation,
799 or a gaming computer. A Bluetooth device connects the static bike to the game for real-time
800 interaction.

801 Supplemental File 3: Characteristics of the foods presented in the computerised food
802 preference task (.docx). The table provides the detailed composition of the foods displayed
803 in the task, including energy density and macronutrient composition derived from the food
804 packaging, grams served, and portion displayed.

805 Supplemental File 4: Information about virtual reality provided during the familiarisation
806 session prior to first exposure to virtual reality (.docx)

Supplemental File 1

Study flow chart

Appendix B

VR exergames offered to participants.

The games are part of the VirZoom Arcade, accessible directly via some VR headsets (e.g. Oculus Quest), a Playstation, or a gaming computer. A Bluetooth device connects the static bike to the game for real-time interaction.

1. Cowboy: Jailbreak!

Game objective: To use commands on the VirZoom bike along with body movement to direct the rope and catch escaping bandits. Pedalling speed is reflected by distance to bandits.

Expected intensity level: Comfortable

2. Kayak: Lotus Pond.

Game objective: Use body movements to guide kayak and search for ducks (daytime) or lead fist to underwater gems (night). Pedalling speed reflected in speed of kayak. Commands used to throw food in the water.

Expected intensity level: Comfortable

3. Cycle: Le Tour, Cali Rally.

Game objective: To meet new goals every kilometre cycled (e.g. drafting behind other cyclists to conserve energy, overtaking, maintaining a set speed). There are two versions of this cycling game.

Expected intensity level: Comfortable

4. Race car: Curvy Race, Oval Race.

Game objective: By adjusting cycling speed and using body movement to orient the car, the user aims to win the car race where the competition is controlled by artificial intelligence.

Expected intensity level: Intense

5. Tank: Thunder Bowl.

Game objective: To use commands on the VirZoom bike along with body movement to explore a determine area and destroy enemy tanks controlled by artificial intelligence without getting shot.

Expected intensity level: Moderate

6. Pegasus: Keep Flying, Gate Race and Gem Hunt

Game objective: There are three versions of this game. The first is to keep flying for as long as possible, whereby finding apples facilitates the continuation of flight. The second is to guide the horse across multiple gates. The third entails the exploration of an environment to locate gems.

Speed of cycling enables flight (activated by pressing commands on the VirZoom bike)

Expected intensity level: Moderate-Intense

Appendix C

Characteristics of the foods presented in the computerised food preference task.

Nutritional value derived from the food packaging.

Food	Energy density (kcal/g)	Kcal/g			Grams served (g)	Portion (kcal)
		Fat	Carbs	Protein		
Rice with corn (60%/40%)	1.17	10.98	90.56	16.4	122.82	119.98
Banana	1.03	4.5	92.8	4.8	115.70	119.17
Chicken	1.06	9.9	0	96	113.00	119.78
Tomato & basil pasta	1.46	36.9	90.8	14.8	96.10	140.31
Strawberry trifle dessert	1.47	54	84	8	95.20	139.94
Boiled eggs	1.43	86.4	2	56.4	94.70	135.42
Noodles with katsu sauce (75%/25%)	1.86	55.8	116	10.8	91.00	169.26
Toffee and vanilla ice cream	1.84	58.5	113.2	11.2	88.30	162.47
Tuna and mayonnaise (85%/15%)	1.86	102.6	2	80.4	152.60	166.46
French fries	2.47	86.4	144.4	9.6	77.80	192.17
Apple pie	2.7	94.5	160	10.8	72.40	195.48
Beef burger	2.51	150.3	10.8	59.6	79.00	198.29
Naan bread	2.98	63	192.4	36	77.70	231.55
White bread with Nutella (75%/25%)	3.15	85.95	194.4	31	86.20	240.07
Dutch edam cheese	3.12	216	2	96	76.90	239.93
Ritz crackers	5	207	254	30.8	52.20	261.00
Twix	4.95	215.1	258.4	26.8	52.80	261.36
Pepperami sausage	5.01	396	8.8	104	51.40	257.51

Characteristics of the foods provided in the post-exercise ad libitum buffet meal.

Food	Energy density (kcal/g)	Kcal/g			Grams served (g)	Portion served (kcal)	Number of standard servings
		Fat	Carbs	Protein			
White bread	2.39	19.8	182.40	32.4	160	382.4	2
Salted crisps	5.26	287.1	206.00	24.4	75	396	3
Salted pretzels	3.93	37.8	306.80	41.2	90	354	3
Chocolate chip cookies	4.93	215.1	248.00	23.2	67.5	265	4
Strawberry jam	2.54	0.9	248.00	2	92	233.68	4
Raisin cereal bar	3.77	79.2	276.00	17.2	111	510	3
Sliced apple	0.38	4.5	29.60	2	289	108	3
Crunchy peanut butter	6.72	529.2	27.20	105.6	60	403.2	3
Wafer thin ham	1.02	21.6	4.00	74.8	63	63	3
Mild cheddar cheese	4.16	314.1	0.40	101.6	96	400	4
Buttery spread	7.03	711	2.40	0.4	40	210	3

Appendix D

Information about virtual reality provided during the familiarisation session prior to first exposure to virtual reality.

WHAT IS VR?

Virtual Reality (VR) is a computer-generated environment, providing sensory stimuli to our senses. Contrary to "Augmented Reality" (e.g. Pokemon Go), which layers additional information to the real world, VR creates an isolated environment.

This virtual world does not obey the limitations of the real world, giving programmers freedom of putting the users in whatever type of reality they could possibly imagine.

Most current VR experiences generate an output of visual and auditory stimuli via headsets, but in the near future we expect to be able to "feel" the projected virtual objects. An important characteristic of VR is the near real-time feedback provided by the hardware and software, which is essential for the feeling of immersion.

The implications for the gaming industry, as well as for the movie experience, seem obvious, but as research with VR advances, additional applications for VR are emerging. VR can now help patients during physical rehabilitation and has been used for the treatment of mental illnesses such as phobias. Patients can learn to get used to approaching digital spiders and feel comfortable with them or try out flying in a virtual airplane before taking an actual flight.

Improving your workout experience with VR

Let's consider possible ways in which VR may be implemented during exercise to increase physical activity in the general population and, consequently, promote health.

Improving the enjoyability of working out could attract more people to gyms and increase the amount of time they spend engaging in exercise. Imagine kayaking down the Mekong River in Vietnam while rowing on a machine at your local fitness centre. Imagine fighting Mike Tyson instead of a punching bag. Imagine cycling the Tour de France on your stationary bike. However, before we invest in programming the necessary software and constructing the hardware, it is important to find out if the benefits from using VR are worth the additional costs for both health centres and users. VR equipment, as well as its' maintenance, tend to be costly and not all people find it equally appealing. Very little research has been conducted to analyse the effects of using VR on the workout experience, which is why we aim to find out more about it. You are going to help us with this task by participating in our study and sharing your thoughts on the topic. Is VR a good investment to help increase physical activity and the respective health outcomes?