

## Using virtual reality to train inhibitory control and reduce binge eating: A proof-of-concept study

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### ARTICLE INFO

#### Keywords:

Inhibitory control  
Binge eating  
Brain training  
Virtual reality  
Go/no-go

### ABSTRACT

**Objective:** One reason for limited efficacy of treatments for binge eating disorder (BED) and bulimia nervosa (BN) is a failure to directly target deficits in inhibitory control (i.e., the ability to withhold a pre-potent response). Inhibitory control trainings (ICTs; computerized tasks meant to improve inhibitory control) have shown promise but appear not to be powerful enough to generalize to real-world eating behavior or engaging enough for to sustain long-term compliance. Delivering an ICT through virtual reality (VR) technology should increase intervention power because 3D imagery and actual real hand/arm movements are lifelike and may improve compliance because the VR environment is highly engaging. Thus, we created the first-ever VR-based ICT to test its initial feasibility, acceptability, and impact on binge eating.

**Method:** We recruited participants (N = 14) with once-weekly loss-of-control (LOC) eating to use the VR ICT daily, at home, for two weeks, and measured feasibility, acceptability and change in LOC eating at post-intervention and 2-week follow-up.

**Results:** The VR ICT was feasible to construct and deploy, and demonstrated high acceptability and compliance (i.e., 86.8% of daily trainings completed). Users of the VR ICT experienced large decreases in LOC eating at post-intervention and 2-week follow-up.

**Discussion:** Results from this initial pilot indicate that delivering ICT through VR is feasible, acceptable, and is associated with reductions in binge eating. Future study is warranted and should examine whether a VR ICT can serve as a useful adjunct to standard treatment for BN and BED.

### 1. Introduction

Binge eating (consuming large amounts of food within a discrete time period, while experiencing a loss of control) and its manifestations, binge eating disorder (BED) and bulimia nervosa (BN), are debilitating conditions considered to be a major public health issue (Kessler et al., 2013). Loss-of-control (LOC; i.e., the feeling that one cannot stop eating once started) is considered to be the hallmark characteristic of binge eating most associated with distress and functional impairment (Mond, Latner, Hay, Owen, & Rodgers, 2010). Cognitive behavioral therapy (CBT) is considered the first-line treatment for LOC and binge eating. Yet, 50–70% of patients remain fully or partially symptomatic at post-intervention (Peat et al., 2017), suggesting a significant need to improve outcomes. Suboptimal outcomes suggest that existing

interventions fail to adequately address key maintenance factors of LOC eating.

Difficulties with binge eating can be explained as a tug-of-war between “reflective” (i.e., top-down, explicit, logical, goal-oriented) and bottom-up (i.e., bottom-up, quick-acting, implicit, reward-driven) decision-making processes (Hofmann, Friese, & Strack, 2009; Hofmann, Friese, & Wiers, 2008; Strack & Deutsch, 2014). In a dysfunctional system, decisions consistent with long-term goals (e.g., refraining from binge eating) “lose out” to more powerful, faster-acting impulses (e.g., desire for reward or comfort from food). However, in an adaptive system, higher order goals can be prioritized via cognitive control capacities that result in overriding the “impulsive pathway.” In particular, inhibitory control is a cognitive capacity centered in the prefrontal cortex that enables overriding automatic responses to rewarding stimuli,

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such as food. Inhibitory control has strong links to LOC eating (Balodis et al., 2013; Schag, Schönleber, Teufel, Zipfel, & Giel, 2013; Wu, Hartmann, Skunde, Herzog, & Friederich, 2013), suggesting this neuro-cognitive capacity is a promising potential avenue for intervention on LOC eating.

To date, inhibitory control has primarily been trained through tasks through repeated administrations of tasks that measure inhibitory control (e.g., Go/No Go, Stop Signal, antisaccade tasks) in which participants are required to repeatedly inhibit their response towards desirable stimuli. A series of investigations and reviews have demonstrated that inhibitory control training (ICT) programs are efficacious in improving inhibitory control (Spierer, Chavan, & Manuel, 2013; Vinogradov, Fisher, & de Villers-Sidani, 2012), and several have demonstrated transfer of these abilities to real world behavior (e.g., reduction in unhealthy eating in the laboratory) (Houben, 2011; Houben & Jansen, 2011; Houben, Nederkoorn, Wiers, & Jansen, 2011). In particular, several reviews suggest that the Go/No Go (GNG) paradigms (relative to stop signal or other ICT paradigms) appear to be the most efficacious method for promoting reduced food intake in the laboratory (Allom, Mullan, & Hagger, 2016; Jones et al., 2016). Although its specific mechanisms remain unclear, existing accounts theorize that GNG ICT paradigms create automatic “stop” associations with the target being trained (e.g., binge foods) rather than facilitating “top-down” inhibitory control, thereby targeting the “impulsive” rather than “reflective” pathway of decision-making.

While promising overall, ICTs, including those based on the GNG, have overall had limited and mixed success in producing changes in eating behavior outside of the laboratory (Allom et al., 2016; Jones et al., 2016). The lack of meaningful behavior change can be attributed to two related factors: (1) poor approximation to everyday life, as the motion of a keypress in response to images is far removed from real-life behavior (Boendermaker, Peeters, Prins, & Wiers, 2017; Forman et al., 2017; Guerrieri, Nederkoorn, & Jansen, 2012; Houben & Jansen, 2011) and (2) lack of repeated administrations (i.e., most existing studies have implemented single trainings) (Kueider, Parisi, Gross, & Rebok, 2012; Morrison & Chein, 2011; Vinogradov et al., 2012). In other words, for ICTs to achieve the largest possible effect on real-world behavior it is necessary to maximize immersion in the trainings and ensure they are compelling and engaging enough to facilitate frequent use.

Delivering ICT through virtual reality (VR) confers many important advantages over traditional ICTs. First, the more realistic imagery of VR better approximates encountering palatable foods in the natural environment. In samples of individuals with eating disorders (EDs), exposure to 3D images, compared to 2D images, induce greater desires to consume the food (Perpiñá et al., 2013). Additionally exposure to real food and VR food stimuli produce equivalently high arousal (Gorini, Griez, Petrova, & Riva, 2010). Secondly, a VR ICT can be designed to facilitate inhibition of realistic motor movements (e.g., reaching and grabbing), which may increase the potential for transfer to eating behavior. Thirdly, VR induces a “sense of presence”, i.e., a feeling of being immersed (Krijn et al., 2004), which is likely to result in greater adherence with trainings in the long term. In fact, the field recently recognized the potential of VR to enhance treatment for LOC eating specifically (De Carvalho, Dias, Duchesne, Nardi, & Appolinario, 2017), and a recent demonstrated a positive effect of VR-based treatment programs (e.g., exposure based programs) for eating disorders (Clus, Larsen, Lemey, & Berrouguet, 2018). Another recent study demonstrated that individuals a bias (via hand-movements/grabbing) towards food in virtual environments is associated with body mass and attitudes towards food (Schroeder, Lohmann, Butz, & Plewnia, 2016). Therefore, the development and testing of a VR based ICT is a warranted next step for improving treatment outcomes for LOC eating.

As such, we developed and preliminarily tested the feasibility and acceptability of a virtual reality ICT for reducing LOC eating. To our knowledge, this study was the first to modify an inhibitory control training to be delivered in VR format. The VR ICT, which is based on the

GNG paradigm, trains individuals with LOC eating to behaviorally inhibit automatic approach responses to highly palatable foods by cueing them to grab binge foods paired with “no go” cues or not to grab non binge foods when paired with “go” cues within the training. In the current manuscript, we describe the VR ICT and describe the feasibility, acceptability, and preliminary efficacy and mechanism of the VR ICT in a small sample of individuals (N = 14) with clinically significant LOC eating pathology.

## 2. Method

### 2.1. VR ICT design

Because one of the goals of a VR-based ICT was to maximize generalization of inhibitory responses to a “real world” environment (i.e., where a participant is likely to experience urges to binge eat), the training is set at a dining table with bookshelves containing cookbooks and other relevant accessories. In order enable complete focus on the trainings, we opted to have participants complete the training sitting down in front of a virtual table (instead of exploring the virtual world). We also designed the surrounding to be minimalistic in order to avoid distraction. Participants were able to use hand controllers to control the virtual hands (See Fig. 1), which were designed to interact with objects on the virtual table. Distance from the stimuli and size of the stimuli were standardized. As part of the training set-up, participants completed a tutorial that measured their reach and distance from the computer and sensors. Based on their reach length, a “starting place” was created in the training. The training would not start until the participant was in the correct place in space. The binge food stimuli were chosen based on foods known to be common binge foods in the literature (Rosen, Leitenberg, Fisher, & Khazam, 1986; Yanovski et al., 1992) and digitally created as photo-realistic 3D models in Maya 3D modeling software.

The VR ICT was based on a GNG task, in which participants are presented with 3 blocks of 10 trials (i.e., 30 total trials) of stimuli, with 33% of the stimuli being binge foods (i.e. pizza, French fries, brownie, cake, chocolate chip cookie), 33% fruits and vegetables (i.e. apple, orange, green bell pepper, banana, carrot) and 33% neutral items (i.e. cup, bowl, knife, fork, spoon; Fig. 1). Consistent with previous studies, we chose the “Go” stimuli based on items that should be conceptually (and obviously) distinct from the “No Go” stimuli so that implicit learning based on very quick presentation of the stimuli could occur without confusion (i.e., “No Go” to items that are conceptually similar to pizza, French fries, etc.). We decided to include fruits/vegetables as the “Go” stimuli to be consistent with the theme of being in a kitchen setting. Neutral stimuli were other non-food items that can be found in a kitchen. All food stimuli were presented on a plate, with binge food stimuli paired with a yellow plate (“No Go” signal), all fruits/vegetables with a blue plate (“Go” signal), and neutral items paired with “No Go” 50% of the time and “Go” 50% of the time, consistent with validated GNG paradigms (Allom et al., 2016). Having neutral items be paired with “Go” 50% of the time and “No Go” 50% of the time increases the difficulty of the training and also ensures the participant uses the Go and No Go signals (colors of the plate) to cue action, rather than the stimuli itself. The “Go” signal indicated that the participant should, as quickly as possible, reach for and grasp the food (which was either on the left or right edge of the screen) and bring it towards his or her mouth. The “No Go” signal required the participant to withhold a response.

Given evidence that cognitive trainings must be appropriately difficult (but not too difficult) in order to yield the greatest gains (Vinogradov et al., 2012), the difficulty of the task increased as participants’ performance improved. Specifically, the length of time allowed to respond started at 6000 ms (longer than conventional, given that reaching and grabbing is more time-intensive than pressing a key) and decreased by 50 ms each time a block’s accuracy was  $\geq 95\%$ . As the latency to respond to stimuli is decreased, the Go response must initiate more quickly, thus making inhibition of the response more challenging.

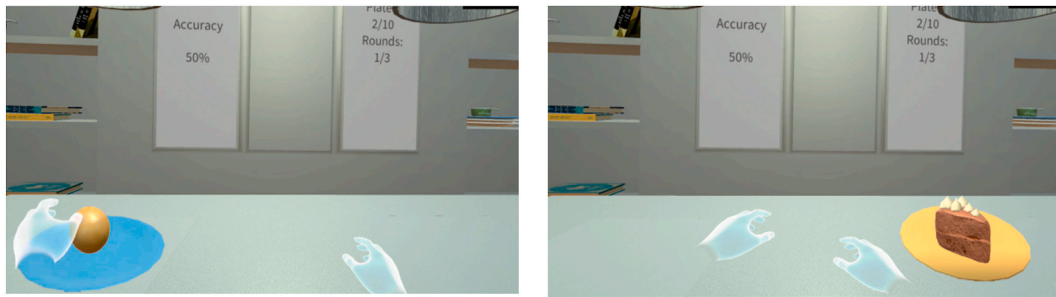


Fig. 1. Screenshots of the trainings.

Latency to respond at the end of a training session was carried over to the next training session.

## 2.2. Pilot study design

**Participants.** The current sample included adults who experienced at least 12 episodes of LOC eating over the preceding three months (assessed via clinical interview), given evidence that LOC is considered the hallmark characteristic of binge eating (Colles, Dixon, & O'Brien, 2008) and that individuals with LOC (regardless of whether binge episodes were subjectively or objectively large) demonstrate deficits in executive functioning, including inhibitory control (Manasse et al., 2014, 2015). Participants were included in the study if they could speak, write, and understand English, were over 18 years of age, had a body mass index (BMI) of 18.0 kg/m<sup>2</sup> or greater, experienced objectively or subjectively large LOC eating episodes once per week or more for the past three months, and if applicable, had stable psychiatric medication for the past three months. Individuals were excluded if they were at acute suicide risk (assessed by trained study staff), were receiving concurrent psychological treatment for LOC eating, were receiving concurrent weight loss treatment, had a co-morbid clinically significant psychological disorder that would require attention beyond the study treatment (e.g., psychotic disorder, substance dependence), had a diagnosis of intellectual disability or autism spectrum disorder, had a history of neurological condition or traumatic brain injury, were pregnant, had a history of bariatric surgery, were currently using a stimulant medication, or had no internet connection at home (necessary for completing the VR ICT).

## 2.3. Procedures

**Recruitment.** Study participants were recruited through clinical referral networks, community announcements, university webpages, and radio advertisements.

**Assessments.** Assessments occurred at baseline, post-intervention, and 2-week follow-up. Baseline and post-intervention assessments took place at the Center for Weight, Eating, and Lifestyles Sciences (WELL Center) at Drexel University, and the two-week follow-up was conducted via phone. Eligibility was confirmed through the Eating Disorders Examination (see Measures). Participants were trained in setting up the VR equipment and completing the VR ICT by study staff. This training involved a demonstration by study staff and subsequent participant completion of full equipment set-up as well as having the participant complete a full training session (3 rounds) so that they could ask questions and become acquainted to the VR technology in the presence of study staff. At post-intervention, LOC eating was assessed, assessors gathered qualitative feedback through an interview, and self-report measures of feasibility and acceptability (TRAQ and TEQ; see measures) were administered. We also administered a Go/NoGo Task and pre- and post-intervention in order to assess the effects of the VR ICT on inhibitory control. Unfortunately, however, a programming error rendered these data unusable and thus we are unable to report on

changes in inhibitory control from pre- to post-intervention. Lastly, we administered self-report impulsivity measures at every time point and a sham taste test that measured eating-related disinhibition at pre- and post-intervention.

**Equipment.** Participants were loaned an Acer Predator Helios 300 Gaming Laptop, and Oculus Rift headset, hand controllers and sensors for the two weeks.

**Training Schedule.** Study participants were instructed to complete one training per day, at home, over the 13 days following the baseline assessment, with the training completed during the assessment counting as the first training session. During the baseline assessment, assessors worked with participants to make a plan for when they would complete the training for each of the remaining 13 days.

## 2.4. Measures

**Eating Disorders Examination (EDE).** The binge module of the EDE was used to measure number of subjective or objective binge episodes over the previous three months (Fairburn, Cooper, & O'Connor, 2014). The EDE is a partially structured clinical interview that was conducted by trained assessors. Given the study length, we assessed for LOC eating episodes over the past two weeks (rather than the typical past 28 days) in order to capture change over the course of the 2-week intervention period and 2-week follow-up.

**Technology Reactions and Acceptance Questionnaire (TRAQ).** Adapted from the Technology Acceptance Model, an adaptation of the TRAQ was used to measure perceived ease-of-use of the at-home ICT (Lee, Kozar, & Larsen, 2003). Also administered are Likert-style satisfaction measures of training difficulty, length, and clarity of instructions (5-point scale from "Completely disagree" to "Completely agree").

**Technology Expectancy Questionnaire (TEQ).** The TEQ was used to measure perceived usefulness (extent to which participants believe the trainings will improve ability to reduce LOC eating) of the at-home ICT will be assessed using an adaptation of the TEQ (Lee et al., 2003).

**Post-Intervention Interview.** Consistent with previous studies (Davis, 1985; Hardy, Willard, Allen, & Bonner, 2013; Lee et al., 2003), we used a semi-structured post-intervention interview to elicit feedback about specific aspects of the VR ICT from participants (e.g. training set-up, training use, food items included, etc.).

**UPPS Impulsive Behavior Scale.** Self-reported impulsivity was measured using the UPPS Impulsive Behavior Scale (UPPS; (Whiteside & Lynam, 2001). This measure is comprised of 59 items assessing an individual's degree of emotion based rash action, sensation seeking, and deficits in conscientiousness.

**Difficulties in Emotion Regulation Scale – Impulse subscale.** Self-reported impulsivity was also measured using the Impulse subscale of the Difficulties in Emotion Regulation Scale (DERS; (Gratz & Roemer, 2004). This subscale assesses an individual's difficulty regulating behavior when distressed.

**Sham Taste Test.** Behavioral eating-related disinhibition was measured via a sham taste test (Allom et al., 2016; Jones et al., 2016; Veling, Aarts, & Stroebe, 2013). Participants were presented with full

plates of four foods (Lays chips, chocolate chip cookies, mini pizza bagels, and mini brownie bites) and asked to rate each food for taste, texture, and overall appeal. The assessor also informed participants that he/she would be stepping out for a few minutes and that they could eat as much of the foods as they liked after making their ratings. After 10 min, the assessor returned. Each plate was weighed before and after the sham taste test to determine the amount of food consumed.

### 3. Results

#### 3.1. Participant characteristics

Participants were 71.4% female ( $n = 10$ ) and were, on average, 46.21 ( $SD = 15.35$ ) years old. On average, participants endorsed 9.86 ( $SD = 7.74$ ) LOC episodes in the past two weeks. Separated by objective and subjective binge episodes, participants reported 5.41 subjective binge episodes ( $SD = 6.84$ ), and 2.91 objective binge episodes ( $SD = 3.22$ ) over the past 2 weeks at baseline. Participants were, on average, in the obese body mass index (BMI) category ( $M = 32.61$ ,  $SD = 5.44$ ). Although our criteria allowed for participants to have a BMI of at least 18.0 kg/m<sup>2</sup>, the range of BMI was 24.41–43.09 and only one participant was below the overweight BMI range. We were unable to include a full diagnostic ED assessment, and thus prevalence of current and past full-threshold ED diagnoses are unknown.

#### 3.2. Feasibility

All participants completed their post-intervention and 2-week follow-up assessments. Average compliance with the trainings was 86.8% (i.e., an average of 12.15 out of 14 daily trainings completed). All but one participant completed at least 10 of the 14 daily trainings.

#### 3.3. Technical difficulties

Participants episodically reported difficulties with VR setup, such as having to re-pair the Bluetooth hand controllers during the initial at home set-up and plugging the sensors and oculus headset into the correct ports on the computer. However, in all cases, a research assistant was able to successfully troubleshoot with the participant. No missed daily trainings resulted from technical difficulties with the VR system. A number of participants reported that they were unable to “grasp” foods with the left hand controller, due to a software programming error.

#### 3.4. Acceptability

Overall, participants rated the VR ICT favorably, e.g., consistently rating that it was easy to use, that it became part of their daily routine, that they looked forward to using it, that it enhanced skills applicable to everyday life (see Table 1), and 78.6% would recommend it to a friend who was trying to reduce LOC eating. However, on average, participants “neither agreed nor disagreed” that the trainings were boring.

**Table 1**  
Summary of acceptability scores.

Item	M (SD)
The training was easy to use	4.21 (.80)
I had fun when using the training program	4.21 (.89)
I looked forward to using the training program	4.14 (.95)
I found the training program to be difficult to understand	1.86 (1.1)
If it were available, I'd continue the training after the study ends	3.64 (1.6)
I found the trainings to be boring	2.57 (1.40)
The skills enhanced in the training apply to my everyday life	3.23 (1.01)

Note: Items were rated on a 1 to 5 Likert scale, with 1 = Completely disagree and 5 = Completely agree.

### 4. Qualitative feedback

Qualitative interviews at post-intervention yielded several themes regarding the engaging nature of the training and perceived mechanisms of the training. Overall, participants felt the training was engaging, with one participant stating: “the 3D aspect of the training was very interactive and interesting.” Participants also reported that they felt the training worked on an explicit level (rather than an implicit, underlying neurocognitive level, with a participant reporting, “[the training] made me stop and think about what [foods] to choose in real life.” Another participant reported that “the physical act of grabbing healthy foods and not grabbing unhealthy foods felt really empowering.” However, participants neither agreed nor disagreed that the trainings were boring and only somewhat agreed that the training enhanced skills applicable to everyday life (i.e. helped them resist urges to binge in real life). Participant suggestions for improvement centered around three themes: (lack of) difficulty, (lack of) variety of foods, and appearance of foods. Although we had created the training such that it became more difficult as participants improved, participants reported the trainings were too easy, even once they reached the most difficult level of the task. Participants also commented that they would like to see a larger variety of foods and that some of the foods (e.g., brownie) were difficult to recognize. Additionally, several participants reported that the binge foods (i.e. the foods on yellow plates) were more appetizing than the healthy foods (i.e. the foods on blue plates), which could be attributable to overall taste preferences for the binge foods.

#### 4.1. Change in LOC eating

See Fig. 2 for a depiction of change in LOC eating across the study period. A non-parametric Friedman test revealed that participants experienced statistically significant decreases in LOC eating (measured over the past two weeks) ( $M_{pre} = 9.86$  [ $SD_{pre} = 7.74$ ],  $M_{post} = 4.71$  [ $SD_{post} = 5.59$ ],  $M_{fu} = 1.93$  [ $SD_{fu} = 2.89$ ]; chi square = 11.14,  $p < .01$ ); notably, LOC eating continued to decrease through the follow-up period.

#### 4.2. Changes in self-report impulsivity and eating-related disinhibition

Friedman tests revealed that impulsivity as measured by the UPPS did not change from baseline to follow-up ( $M_{pre} = 2.47$ ,  $SD_{pre} = .09$ ,  $M_{fu} = 2.48$ ,  $SD_{fu} = .11$ , chi-square = 1.86,  $p = .40$ ,  $d = .09$ ) but impulsivity as measured by the DERS-impulse decreased from pre-intervention to follow-up ( $M_{pre} = 15.86$ ,  $SD_{pre} = 4.69$ ,  $M_{fu} = 14.10$ ,  $SD_{fu} = 3.88$ , chi square = 1.33,  $p = .19$ ,  $d = .40$ ), though the change was not statistically significant. Consumption on the sham taste test decreased to a medium degree ( $M_{pre} = 134.64$ g,  $SD_{pre} = 80.21$ ,  $M_{post} = 98.28$ g,  $SD_{post} = 55.39$ , chi square = 2.57,  $p = .10$ ,  $d = .60$ ). Spearman's correlations demonstrated that changes in UPPS scores, DERS-impulse scores and taste test consumption had moderate-to-large associations with changes in LOC eating ( $r_{UPPS} = .37$ ,  $p_{UPPS} = .20$ ,  $r_{DERS} = .52$ ,  $p_{DERS} = .06$ ,  $r_{tastetest} = .59$ ,  $p_{tastetest} = .03$ , respectively).

### 5. Discussion

To our knowledge, this proof-of-concept trial is the first to develop and evaluate the initial feasibility, acceptability, and preliminary impact of a VR-based ICT. In a small sample of individuals who demonstrated clinically significant loss-of-control eating at baseline, results suggest that the VR ICT was feasible to implement and completing the training daily for two weeks was found to be acceptable by participants.

Specifically, participants reported that the training was easy to use, that it became part of their daily routine, and that they looked forward to using it. On average, participants missed just one training per week, consistent with existing trials of ICTs demonstrating that participants (in the context of being compensated for a research trial) are generally willing to complete daily 10–15 min trainings (Allom et al., 2016).

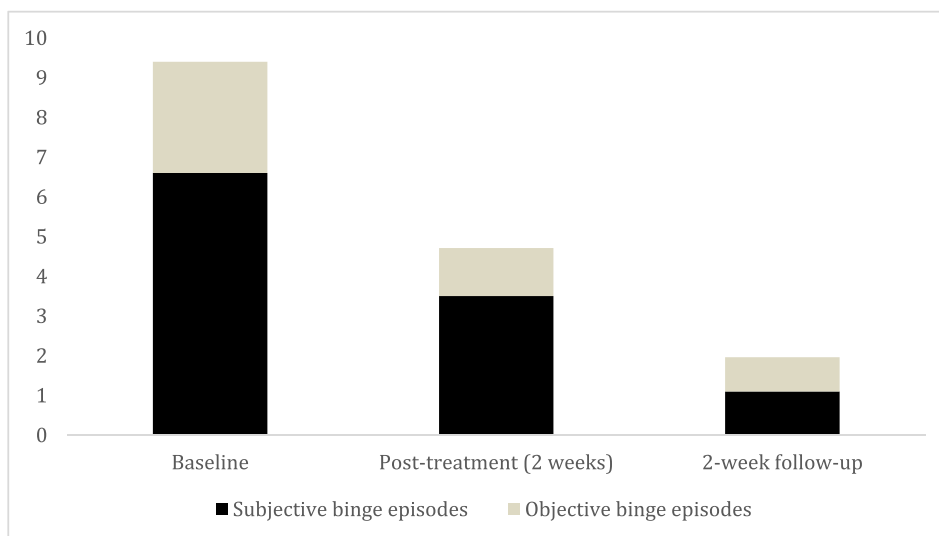


Fig. 2. Episodes of LOC eating over the past 2 weeks.

However, the current study builds on these findings because participants in the current study were highly adherent to an ICT that involved taking home and using equipment (e.g., gaming laptop, VR headset and sensor towers) that they did not own, as opposed to a simple computer/smartphone-based task that they could complete on a device already present in their own homes. In other words, the burden of completing the trainings in VR, rather than in simple computerized format, did not appear to negatively impact compliance with the daily trainings. These findings underscore the potential disseminability of VR-based ICTs, particularly as cheap, standalone headsets become more widely adopted.

Participants also gave feedback that provide direction for improving the next iteration of the VR ICT. For example, participants did not find the training to be particularly engaging (i.e., the trainings were somewhat boring), only somewhat agreed that the training enhanced skills applicable to everyday life (i.e., helped them resist urges to binge in real life), and found the foods presented in the trainings to be unattractive. Additionally, many participants reported that there were limited foods in the trainings and reported wanting to see greater variety in the foods displayed, including their specific binge foods in the training. To reduce boredom and increase engagement, future iterations of the training should: (1) increase the difficulty of the trainings, as many participants reported that the training felt too slow, (2) increase the attractiveness and variety of foods present in the trainings, (3) increase personalization of foods, and (4) include additional “levels” and scenarios in which to practice inhibitory control (e.g., restaurant, grocery store). Such enhancements would likely make the ICT more powerful and more engaging (thereby likely increasing the likelihood of long-term usage). In an ongoing trial, our team is using participants’ most-common binge foods to personalize ICT trainings (Manasse et al., 2020), which may increase engagement and reports of transfer of the trainings to everyday life. Another potential avenue for increasing engagement and liking (and decreasing the boringness) of the VR ICT is to add gamification features (e.g., obtaining badges, points) (Forman et al., 2018; Lumsden, Edwards, Lawrence, Coyle, & Munafò, 2016). However, research regarding the effects of gamification on enhancing engagement and efficacy of neurocognitive training programs is mixed (Forman et al., 2019; Mishra, Anguera, & Gazzaley, 2016; Prins, DAVIS, Ponsioen, Ten Brink, & Van Der Oord, 2011). As such, the effects of gamifying a VR-based ICT are unknown. With regards to the suboptimal “transfer to everyday life” ratings, these are difficult to interpret, given that the trainings are designed to operate on an implicit, rather than explicit level. Interestingly, in contrast with these quantitative ratings, some participants

qualitatively reported that the trainings improved explicit decision-making ability, which could be explained by demand effects (i.e., knowing that the training is meant to help decrease binge eating) or by observing increased ease in refraining from binge eating. It is possible that increasing the variety and personalization of the foods, in addition to including additional VR settings (e.g., restaurant, work, bedroom) could increase the ability to the ICT to transfer to everyday eating behavior.

Participants experienced large reduction in loss-of-control eating episodes over the two weeks of active training, and reductions in LOC eating continued during the two-week follow-up period. Despite the lack of a control group, the fact that participants experienced continued reduction in LOC eating during the follow-up period is encouraging. Although our measurement of mechanisms was flawed without useable GNG assessment data, use of the VR ICT was associated with small-to-medium decreases in impulsivity/eating-related disinhibition on two of our three measures. Furthermore, changes in impulsivity and eating-related disinhibition were moderately associated with changes in LOC eating, indicating that changes in impulsivity-related targets may be related to improvements in LOC eating. Future studies should test the efficacy and mechanisms of the VR ICT during longer active training and follow-up periods and use more robust mechanistic variables.

The current study was characterized by several strengths. First, we were the first to develop a VR-based ICT and did so in such a way that participants were able to easily complete trainings at home. Second, we tested effects in a clinical sample; most ICTs have been tested in healthy, non-clinical samples who are unlikely to have deficits in inhibitory control (Allom et al., 2016). Thirdly, participants completed the training repeatedly over two weeks (as opposed to a single-session laboratory design), consistent with a body of literature suggesting that in order for neurocognitive trainings to have maximum effect, they need to be completed repeatedly (Jones et al., 2016).

Despite the novelty and strengths of the current study, results must be interpreted in the context of several limitations. First, we were limited by a small sample and no control group, which precludes our ability to derive strong conclusions from our results. For example, participants were neutral on how boring the training was to complete; future research should compare whether the VR ICT is more or less boring than a computerized version. We also relied on effect sizes rather than statistical significance for interpretation of results. Due to a technical error rendering our data not usable, we were unable to examine the effects of the VR ICT on inhibitory control as measured by a standard Go/No Go task. The lack of behavioral inhibitory control data prevent

our ability to determine whether the VR ICT worked through its putative mechanism. A critical future question will be to examine whether adaptation of the standard Go/NoGo to VR format (e.g., grabbing food with hands vs key press) changes the mechanism through which the training works. Additionally, we only tested the training for a two-week period; future studies should evaluate response to a longer training duration to determine an optimal “dose” of ICT and the durability of its effects when daily training stops or less frequent “booster” sessions are prescribed. Future studies should also compare the efficacy of typical computer-based ICT vs VR ICT and consider pairing VR ICT with a self-help CBT to create a more comprehensive disseminable treatment package. Lastly, the present study lent expensive VR equipment in addition to a gaming laptop to participants; future studies should aim to develop VR-based programs that are compatible with cheap, standalone VR headsets in order to increase accessibility.

In conclusion, using the VR ICT was associated with reductions in binge episodes in individuals with clinically significant LOC eating. Additionally, the VR-based trainings were found to be acceptable to participants. A future randomized trial is necessary to determine the efficacy of a VR-based ICT.

### Author contributions

This work was supported by a Pennsylvania Commonwealth University Research Enhancement (CURE) and a grant from the National Institute of Diabetes, Digestive, and Kidney Diseases (K23DK124514) to Dr. Stephanie Manasse.

S.M. designed the experiment in consultation with A.J. J.Z. and E.F., analyzed the data, and contributed to the written manuscript. E.L. collected the data, and contributed to the written manuscript. All authors have read and approved the final manuscript.

### Declaration of competing interest

None of the authors report a conflict of interest. All study procedures were approved by the Drexel University Institutional Review Board.

### References

- Allom, V., Mullan, B., & Hagger, M. (2016). Does inhibitory control training improve health behaviour? A meta-analysis. *Health Psychology Review*, 10(2), 168–186.
- Balodis, I. M., Molina, N. D., Kober, H., Worhunsky, P. D., White, M. A., Grilo, C. M., et al. (2013). Divergent neural substrates of inhibitory control in binge eating disorder relative to other manifestations of obesity. *Obesity*, 21(2), 367–377.
- Boendermaker, W. J., Peeters, M., Prins, P. J., & Wiers, R. W. (2017). Using serious games to (re) train cognition in adolescents. In *Serious games and edutainment applications* (pp. 307–321). Springer.
- Clus, D., Larsen, M. E., Lemey, C., & Berrouguet, S. (2018). The use of virtual reality in patients with eating disorders: Systematic review. *Journal of Medical Internet Research*, 20(4), e157.
- Colles, S. L., Dixon, J. B., & O'Brien, P. E. (2008). Loss of control is central to psychological disturbance associated with binge eating disorder. *Obesity*, 16(3), 608–614.
- Davis, F. D. (1985). *A technology acceptance model for empirically testing new end-user information systems: Theory and results*. Massachusetts Institute of Technology.
- De Carvalho, M. R., Dias, T. R. d. S., Duchesne, M., Nardi, A. E., & Appolinario, J. C. (2017). Virtual reality as a promising strategy in the assessment and treatment of bulimia nervosa and binge eating disorder: A systematic review. *Behavioral Sciences*, 7(3), 43.
- Fairburn, C. G., Cooper, Z., & O'Connor, M. (2014). *The eating disorder examination* (Vol 17). Edition.
- Forman, E. M., Goldstein, S. P., Flack, D., Evans, B. C., Manasse, S. M., & Dohat, C. (2017). Promising technological innovations in cognitive training to treat eating-related behavior. *Appetite*.
- Forman, E. M., Goldstein, S. P., Flack, D., Evans, B. C., Manasse, S. M., & Dohat, C. (2018). Promising technological innovations in cognitive training to treat eating-related behavior. *Appetite*, 124, 68–77.
- Forman, E. M., Manasse, S. M., Dallal, D. H., Crochiere, R. J., Loyka, C. M., Butryn, M. L., et al. (2019). Computerized neurocognitive training for improving dietary health and facilitating weight loss. *Journal of Behavioral Medicine*, 1–12.
- Gorini, A., Griez, E., Petrova, A., & Riva, G. (2010). Assessment of the emotional responses produced by exposure to real food, virtual food and photographs of food in patients affected by eating disorders. *Annals of General Psychiatry*, 9(1), 30.
- Gratz, K. L., & Roemer, L. (2004). Multidimensional assessment of emotion regulation and dysregulation: Development, factor structure, and initial validation of the difficulties in emotion regulation scale. *Journal of Psychopathology and Behavioral Assessment*, 26(1), 41–54.
- Guerrieri, R., Nederkoorn, C., & Jansen, A. (2012). Disinhibition is easier learned than inhibition. The effects of (dis) inhibition training on food intake. *Appetite*, 59(1), 96–99.
- Hardy, K. K., Willard, V. W., Allen, T. M., & Bonner, M. J. (2013). Working memory training in survivors of pediatric cancer: A randomized pilot study. *Psycho-Oncology*, 22(8), 1856–1865.
- Hofmann, W., Friese, M., & Strack, F. (2009). Impulse and self-control from a dual-systems perspective. *Perspectives on Psychological Science*, 4(2), 162–176.
- Hofmann, W., Friese, M., & Wiers, R. W. (2008). Impulsive versus reflective influences on health behavior: A theoretical framework and empirical review. *Health Psychology Review*, 2(2), 111–137.
- Houben, K. (2011). Overcoming the urge to splurge: Influencing eating behavior by manipulating inhibitory control. *Journal of Behavior Therapy and Experimental Psychiatry*, 42(3), 384–388.
- Houben, K., & Jansen, A. (2011). Training inhibitory control. A recipe for resisting sweet temptations. *Appetite*, 56(2), 345–349.
- Houben, K., Nederkoorn, C., Wiers, R. W., & Jansen, A. (2011). Resisting temptation: Decreasing alcohol-related affect and drinking behavior by training response inhibition. *Drug and Alcohol Dependence*, 116(1), 132–136.
- Jones, A., Di Lemma, L. C., Robinson, E., Christiansen, P., Nolan, S., Tudur-Smith, C., et al. (2016). Inhibitory control training for appetitive behaviour change: A meta-analytic investigation of mechanisms of action and moderators of effectiveness. *Appetite*, 97, 16–28.
- Kessler, R. C., Berglund, P. A., Chiu, W. T., Deitz, A. C., Hudson, J. I., Shahly, V., et al. (2013). The prevalence and correlates of binge eating disorder in the world health organization world mental health surveys. *Biological Psychiatry*, 73(9), 904–914.
- Krijn, M., Emmelkamp, P. M., Biemond, R., de Ligny, C. d. W., Schuemie, M. J., & van der Mast, C. A. (2004). Treatment of acrophobia in virtual reality: The role of immersion and presence. *Behaviour Research and Therapy*, 42(2), 229–239.
- Kueider, A. M., Parisi, J. M., Gross, A. L., & Rebok, G. W. (2012). Computerized cognitive training with older adults: A systematic review. *PLoS One*, 7(7), Article e40588.
- Lee, Y., Kozar, K. A., & Larsen, K. R. (2003). The technology acceptance model: Past, present, and future. *Communications of the Association for Information Systems*, 12(1), 50.
- Lumsden, J., Edwards, E. A., Lawrence, N. S., Coyle, D., & Munafò, M. R. (2016). Gamification of cognitive assessment and cognitive training: A systematic review of applications and efficacy. *JMIR serious games*, 4(2), e11.
- Manasse, S. M., Forman, E. M., Ruocco, A. C., Butryn, M. L., Juarascio, A. S., & Fitzpatrick, K. K. (2015). Do executive functioning deficits underpin binge eating disorder? A comparison of overweight women with and without binge eating pathology. *International Journal of Eating Disorders*, 48(6), 677–683.
- Manasse, S. M., Juarascio, A. S., Forman, E. M., Berner, L. A., Butryn, M. L., & Ruocco, A. C. (2014). Executive functioning in overweight individuals with and without loss-of-control eating. *European Eating Disorders Review*, 22(5), 373–377.
- Manasse, S. M., Lampe, E. W., Gillikin, L., Payne-Reichert, A., Zhang, F., Juarascio, A. S., et al. (2020). The project REBOOT protocol: Evaluating a personalized inhibitory control training as an adjunct to cognitive behavioral therapy for bulimia nervosa and binge-eating disorder. *International Journal of Eating Disorders*, 53(6), 1007–1013.
- Mishra, J., Anguera, J. A., & Gazzaley, A. (2016). Video games for neuro-cognitive optimization. *Neuron*, 90(2), 214–218.
- Mond, J. M., Latner, J. D., Hay, P., Owen, C., & Rodgers, B. (2010). Objective and subjective bulimic episodes in the classification of bulimic-type eating disorders: Another nail in the coffin of a problematic distinction. *Behaviour Research and Therapy*, 48(7), 661–669.
- Morrison, A. B., & Chein, J. M. (2011). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychonomic Bulletin & Review*, 18(1), 46–60.
- Peat, C. M., Berkman, N. D., Lohr, K. N., Brownley, K. A., Bann, C. M., Cullen, K., et al. (2017). *Comparative effectiveness of treatments for binge-eating disorder: Systematic review and network meta-analysis*. European eating disorders review.
- Perpiñá, C., Roncero, M., Fernández-Aranda, F., Jiménez-Murcia, S., Forcano, L., & Sánchez, I. (2013). Clinical validation of a virtual environment for normalizing eating patterns in eating disorders. *Comprehensive Psychiatry*, 54(6), 680–686.
- Prins, P. J., Dovers, S., Ponsoen, A., Ten Brink, E., & Van Der Oord, S. (2011). Does computerized working memory training with game elements enhance motivation and training efficacy in children with ADHD? *Cyberpsychology, Behavior, and Social Networking*, 14(3), 115–122.
- Rosen, J. C., Leitenberg, H., Fisher, C., & Khazam, C. (1986). Binge-eating episodes in bulimia nervosa: The amount and type of food consumed. *International Journal of Eating Disorders*, 5(2), 255–267.
- Schag, K., Schönleber, J., Teufel, M., Zipfel, S., & Giel, K. (2013). Food-related impulsivity in obesity and Binge Eating Disorder—a systematic review. *Obesity Reviews*, 14(6), 477–495.
- Schroeder, P. A., Lohmann, J., Butz, M. V., & Plewnia, C. (2016). Behavioral bias for food reflected in hand movements: A preliminary study with healthy subjects. *Cyberpsychology, Behavior, and Social Networking*, 19(2), 120–126.
- Spierer, L., Chavan, C. F., & Manuel, A. L. (2013). Training-induced behavioral and brain plasticity in inhibitory control. *Frontiers in Human Neuroscience*, 7.
- Strack, F., & Deutsch, R. (2014). The reflective–impulsive model. *Dual-process theories of the social mind*, 92–104.

- Veling, H., Aarts, H., & Stroebe, W. (2013). Using stop signals to reduce impulsive choices for palatable unhealthy foods. *British Journal of Health Psychology*, *18*(2), 354–368.
- Vinogradov, S., Fisher, M., & de Villers-Sidani, E. (2012). Cognitive training for impaired neural systems in neuropsychiatric illness. *Neuropsychopharmacology*, *37*(1), 43–76.
- Whiteside, S. P., & Lynam, D. R. (2001). The five factor model and impulsivity: Using a structural model of personality to understand impulsivity. *Personality and Individual Differences*, *30*(4), 669–689.
- Wu, M., Hartmann, M., Skunde, M., Herzog, W., & Friederich, H.-C. (2013). Inhibitory control in bulimic-type eating disorders: A systematic review and meta-analysis. *PLoS One*, *8*(12), Article e83412.
- Yanovski, S. Z., Leet, M., Yanovski, J. A., Flood, M.n., Gold, P. W., Kissileff, H. R., et al. (1992). Food selection and intake of obese women with binge-eating disorder. *American Journal of Clinical Nutrition*, *56*(6), 975–980.