Published in final edited form as:

Appetite. 2018 May 01; 124: 68–77. doi:10.1016/j.appet.2017.04.011.

Promising technological innovations in cognitive training to treat eating-related behavior

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Abstract

One potential reason for the suboptimal outcomes of treatments targeting appetitive behavior, such as eating and alcohol consumption, is that they do not target the implicit cognitive processes that may be driving these behaviors. Two groups of related neurocognitive processes that are robustly associated with dysregulated eating and drinking are attention bias (AB; selective attention to specific stimuli) and executive function (EF; a set of cognitive control processes such as inhibitory control, working memory, set shifting, that govern goal-directed behaviors). An increasing body of work suggests that EF and AB training programs improve regulation of appetitive behaviors, especially if trainings are frequent and sustained. However, several key challenges, such as adherence to the trainings in the long term, and overall potency of the training, remain. The current manuscript describes five technological innovations that have the potential to address difficulties related to the effectiveness and feasibility of EF and AB trainings: (1) deployment of training in the home, (2) training via smartphone, (3) gamification, (4) virtual reality, and (5) personalization. The drawbacks of these innovations, as well as areas for future research, are also discussed. The above-mentioned innovations are likely to be instrumental in the future empirical work to develop and evaluate effective EF and AB trainings for appetitive behaviors.

Keywords

executive function; computer training; eating; alcohol; digital health behavior change

Introduction

Outcomes from existing gold-standard behavioral treatments for obesity are sub-optimal, typically only producing 5-10% of body weight lost at one year post-treatment, with complete weight regain occurring for most individuals at five years post-intervention (Butryn, Webb, & Wadden, 2011). Similarly, even our best treatments for alcohol abuse are of limited efficacy (Dutra et al., 2008). One potential reason for these poor outcomes is that appetitive behavior is driven less by the explicit decision-making factors targeted by

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traditional treatments, and more by implicit (automatic, fast-acting, unconscious) processes and the executive functions (EF) that regulate these processes.

Two groups of such neurocognitive processes, attention bias (AB) and EF, are of special interest, given their strong connection with dysregulated eating behavior. Attention bias (i.e., preferential or selective attention to one type of information) is an unconscious cognitive process that appears to be associated with eating behavior (Castellanos et al., 2009). In particular, a large body of research suggests that increased AB towards palatable food cues predispose individuals to consume those foods (Braet & Crombez, 2003; Castellanos et al., 2009; Graham, Hoover, Ceballos, & Komogortsev, 2011; Long, Hinton, & Gillespie, 1994; Nijs, Franken, & Muris, 2010; Nijs, Muris, Euser, & Franken, 2010). For example, those with higher AB towards palatable food may be quicker to attend to unhealthy choices available in a grocery store. EF, by contrast, consists of a set of cognitive control processes (e.g., inhibitory control, working memory, set shifting) that govern higher-order, goal-directed behavior (Miyake et al., 2000). Deficits in EF are robustly associated with dysregulated eating behaviors (which, we define as including eating and drinking; Bechara & Martin, 2004; Manasse et al., 2015; Smith, Hay, Campbell, & Trollor, 2011). For example, deficits in inhibitory control (i.e., the ability to withhold an automatic response) may make adherence to calorie goals difficult, especially in the presence of palatable food/drink (Brockmeyer et al., 2016). Self-regulatory goals (e.g., to maintain a healthy diet) are also compromised by poor working memory (i.e., the ability to keep goal-relevant information in mind in the face of distractors; Hofmann, Schmeichel, & Baddeley, 2012).

In light of the above relationships between EF, AB, and eating, research has begun to investigate the utility of training inhibitory control, working memory, and attention bias in the hopes that doing so will improve regulation of eating-related behavior. The usual protocol for EF training involves the use of a computer to repeatedly administer tasks that become increasingly difficult as the participant improves. These protocols have proven successful in many respects, though questions remain about adherence and behavioral transfer (especially long-term) to changing eating behavior. The typical protocol for inhibitory control training is a stop-start signal task or go/no-go task in which participants are repeatedly asked to inhibit responses to stimuli when presented with a “stop” cue. The typical protocol for training working memory typically includes either a letter or number digit span task (in which participants are asked to repeat and/or manipulate a series of numbers) or a visuospatial task (in which participants are asked to remember the order of presentation of visual stimuli). The typical protocol for attention bias modification (ABM) is a visual dot probe task, in which participants are continually asked to respond to one of two stimuli; in the training version of the task, participants are repeatedly asked to respond to (and thus attend to) non-food stimuli being presented.

Several meta-analyses support the preliminary promise of EF and AB trainings for changing appetitive behaviors, but also show that effects tend to be short-term and small in size (Allom, Mullan, & Hagger, 2016; Jones et al., 2016; Turton, Bruidegom, Cardi, Hirsch, & Treasure, 2016). Two key challenges facing EF training and ABM for eating behavior are adherence to demanding training regimens and the ability to transfer gains to real-world eating decisions, especially in the longer term. Evidence suggests that EF trainings and

ABM need to occur at a high frequency and/or intensity in order to have a large and lasting impact on behavior (Chein & Morrison, 2010; Kueider, Parisi, Gross, & Rebok, 2012; Richmond, Morrison, Chein, & Olson, 2011; Vinogradov, Fisher, & de Villers-Sidani, 2012). While the need for high frequency and/or intensity trainings is not a problem in and of itself, it begs the question of whether individuals are able to maintain adherence to a daily training prescription. Research in related fields suggests that individuals are often non-adherent to daily prescriptions, whether as simple as taking a pill (Tamblyn, Egualé, Huang, Winslade, & Doran, 2014) or as complicated as daily calorie self-monitoring on a smartphone (Laing et al., 2014). Although there is little evidence regarding long-term adherence to repeated EF and ABM trainings, findings thus far suggest that adherence can suffer because the training tasks are repetitive and boring.

The second main challenge facing EF trainings and ABM is their ecological validity, i.e., translation to real-world behavior. Some research suggests that EF trainings only produce limited “transfer” (i.e., only to in-lab eating behavior immediately following, or even only to response to computerized stimuli), likely because they employ “symbolic” representations of food and are largely not personalized to the individual (Guerrieri, Nederkoorn, & Jansen, 2012; Houben, 2011). Thus, innovations of EF trainings and ABM are promising to the extent that they can increase adherence to repeated training bouts and increase the external validity of training.

The aim of the current manuscript is to review five innovations being utilized or likely to be utilized in the near future in EF training and ABM of eating behaviors: (1) deployment of training in the home, (2) training via smartphone, (3) gamification, (4) virtual reality, and (5) personalization. These innovations are meant to target either or both of the challenges described above. As such, we conducted a systematized literature review in online search engines PsychINFO and PubMed using search terms for EF/attention bias (attention* bias, cognitive, executive function*, working memory, inhibit* control, set-shift*, task switch*, response inhibition, stop signal, go-no-go, impulsivity), training (training, modification, retraining, retraining, game), eating-related (food, drink, alcohol, weight, overweight, overeating, obesity, snack, eating, weight loss) and innovative methods (virtual reality, simulation, virtual world, gamif*, remote, home computer, web, internet, smartphone, application, app, phone, Android, iPhone, personaliz*, tailor*, custom*, match*, individualiz*). Studies were selected for inclusion in the review if they discussed one of the five innovations referenced above in the context of EF/ABM training. In discussing extant work in these areas, we comment specifically on the extent to which empirical findings demonstrate how the innovation enhanced the efficacy of the intervention on real-world eating/drinking behavior, advantages and disadvantages of the innovation and future research directions. See Table 1 for a summary of these aims for each technological innovation.

Deploying EF Trainings/ABM via Home Computer

As evidence for the necessity of repeated EF trainings/ABM continues to mount (Beard, Sawyer, & Hofmann, 2012; Chein & Morrison, 2010; Hakamata et al., 2010; Kueider et al., 2012; Richmond et al., 2011; Vinogradov et al., 2012), it is clear that finding a means to

deliver remote training could enhance the feasibility and disseminability of EF and AB training programs. With the ubiquity of computer and Internet access, it is now possible to implement EF training programs remotely, e.g., on a home computer, with the same quality and reliability as in-lab training sessions. The ease of remote EF trainings makes continued repetition possible and, as such, could 1) increase effectiveness through increased dose of training and 2) maintain gains made during intervention through periodic follow-up training sessions.

Potential Advantages to Adherence and Efficacy

Approximately 84% of U.S. households own a computer and 73% of households have connected to the Internet, which is the primary method of disseminating home computer-based EF trainings. Therefore, home-based trainings appear to be easily disseminable to the majority of the population. Importantly, home computer-based trainings have the advantage of convenience and so the presumed advantage of compliance. Users are more likely to engage in repeated computerized trainings if they are convenient and easy to use (Rainie & Cohn, 2014). Compliance levels are critical because dosage is directly related to effectiveness (Allom et al., 2016). Further, home-based trainings offer the promise of extending the efficacy of EF trainings and ABM through less frequent “booster sessions” on a weekly or monthly basis that could allow participants to maintain gains made during active training phases (Lawrence, O'Sullivan, et al., 2015).

Potential Limitations

While home-based trainings present a distinct advantage of increased ease of dissemination, they also necessitate high levels of motivation in the absence of external accountability (e.g., appointments for in-lab trainings, contact with study staff, payment for study participation). For example, Houben and colleagues (2016) found that dietary restraint moderated the effect of their working memory training on food intake. They postulated that, because these individuals were highly motivated to be restricting their food intake, they were likely more receptive and consistent with trainings (Houben, Dassen, & Jansen, 2016). Similarly, Boutelle and colleagues (2016) believed that participant motivation and buy-in was key for study retention. Unfortunately, because computerized EF/AB trainings are not highly face valid, study staff must carefully convey the importance of training compliance (i.e., foster participant buy-in) without inducing demand characteristic (Boutelle, Monreal, Strong, & Amir, 2016). Lastly, it is possible that the variability of individual's home computers (e.g., processing speed, monitor size, operating system) could affect the reliability of the trainings. In sum, the major limitation with remote/home-based computerized EF/AB trainings is that effectiveness may be based on individual participant characteristics that are difficult to control outside of lab settings.

Empirical Evidence

Several studies have investigated the acceptability and effectiveness of repeated home computer-based EF training administrations. Both working memory (Houben, Wiers, & Jansen, 2011) and ABM (Wiers et al., 2015) trainings have been successfully deployed on Web platforms from home computers to reduce alcohol consumption.

There has been one study to date that has examined a remote working memory training on eating behavior, and findings revealed that this training (delivered over the course of 20 to 25 sessions) reduced psychopathological eating-related thoughts and emotional eating but not food intake or body weight (Houben et al., 2016). With regards to ABM of food consumption and cravings, one study has investigated the impact of home-based ABM trainings on overweight/obese individuals who binge eat. The intervention, comprised of a series of at-home and in-lab training sessions, produced weight loss and decreases in binge eating behavior (as well as changes in attention bias; Boutelle et al., 2016). Taken together, these preliminary findings and the success of repeated in-lab training paradigms (Kakoschke, Kemps, & Tiggemann, 2014; Kemps, Tiggemann, & Hollitt, 2014, 2016; Kemps, Tiggemann, Orr, & Gear, 2014; Werthmann, Field, Roefs, Nederkoorn, & Jansen, 2014) indicate that remotely delivered ABM has the potential to create lasting changes in eating behavior.

Lastly, the majority of literature dedicated to the utility of remote trainings has been conducted in the area of inhibitory control. Several studies have shown that home computer-administered inhibitory control trainings can produce significant weight losses and changes in eating behavior (Forman et al., 2016; Lawrence, O'Sullivan, et al., 2015; Veling, van Koningsbruggen, Aarts, & Stroebe, 2014). In sum, preliminary evidence indicates that remote methods are efficient and effective in delivering repeated EF trainings focused on appetitive behaviors.

Despite the importance of adherence to EF trainings, there is a paucity of research focused on compliance with home EF/AB training. The small body of literature on home-based EF training indicates that participants do tend to be relatively compliant with study procedures. For example, Houben and colleagues (2011) found that participants completed an average of 24.50 out of the 25 requested working memory trainings. Similarly, 82% of participants completed all four inhibitory control trainings in a study conducted by Lawrence and colleagues (2015).

One distinct advantage of home computer-based trainings is the flexibility for participants to complete sessions at times that are convenient for them. Preliminary evidence indicates that having substantial amounts of time to complete trainings (i.e., 2-3 days) independently and in a flexible manner could benefit adherence to training protocols (Houben & Jansen, 2011; Lawrence, O'Sullivan, et al., 2015). Conversely, when the schedule for completing inhibitory control trainings was more rigorous (i.e., completing once per day for three days in a row), participant compliance suffered (Forman et al., 2016). Though these are only a few examples, the pattern is consistent with the notion that adherence worsens as perceptions of burden increase (Eysenbach, 2005).

Future Directions

While preliminary evidence suggests that remote EF/AB trainings are effective, additional research is necessary to replicate and extend previous findings. For instance, while previous findings suggest that remote trainings produce effects that are equivalent in size to training that take place in-lab (Allom et al., 2016; Forman et al., 2016; Lawrence, O'Sullivan, et al., 2015; Veling et al., 2014), no direct comparison of effects have been conducted. Thus, it

remains possible that differences in computer and monitor hardware and surrounding environment could impact the strength of remote training effects relative to in-lab trainings. Further, the moderators of effectiveness for both home-based and in-lab trainings (such as motivational factors, markers of severity) is a research area that remains virtually untouched (Houben et al., 2016). It may be useful in the future to match participants to the training setting that is likely to work best given their strengths, deficits, and preferences. Lastly, given that the strongest argument for remote trainings is the possibility for enhanced disseminability and compliance, more research is needed on the factors that impact adherence to training timing and frequency recommendations.

Smartphone apps

One method to improve adherence to EF trainings, and thus effectiveness, could be to deploy them via smartphone application (app). Smartphones are owned by a rapidly-increasing majority (77% in the United States) and are kept on-person most of the day (Center, 2017; Deloitte, 2016). Thus, smartphone delivered EF training may be more generalizable than other modalities, in that they can be accessed in environments where EF skills may directly impact eating behaviors and that their convenience may encourage a higher frequency of training.

Potential Advantages to Adherence and Efficacy

In addition to their ubiquity, smartphones can provide novel channels for training optimization and engagement such as haptic or tactile feedback, which some research suggests could reduce cognitive load and increase mobile app efficiency, especially in situations where complex visual and cognitive processing is required (Heikkinen, Olsson, & Väänänen-Vainio-Mattila, 2009). Examples of haptic interaction include a user receiving tactile feedback (e.g., phone vibration) after completing a task that requires touching a phone's screen.

Potential Limitations

Several concerns about smartphones as an EF training tool bear mention. For example, smartphone app training may come with decreased focus and attention, given the possibility that trainings will be completed around other people or during cognitively demanding activities (Lawrence, O'Sullivan, et al., 2015). Given the importance of stimulus recognition and clarity in EF trainings, screen size is another major concern that requires empirical study (Lawrence, O'Sullivan, et al., 2015).

Empirical Evidence

Very few smartphone apps to train EF for eating-related behavior currently exist. One such app is *NoGo*, an inhibitory control training for unhealthy eating, smoking and alcohol (Blackburne, Rodriguez, & Johnstone, 2016). In a study of *NoGo*, overweight participants interested in improving their diets used the app for 10 one-minute occasions per day for 14 days, and experienced significant reductions in unhealthy food consumption relative to controls (Blackburne et al., 2016).

Evaluations of EF phone-based trainings for *non*-eating behaviors may offer insight into the promise of eating-related apps. Findings thus far have been mixed. For example, one study examining phone-based training for social anxiety reports small effect sizes and a mix of significant and non-significant differences in attention bias scores (Enock, Hofmann, & McNally, 2014). Another study investigating the effects of smartphone-based cognitive training games on the executive functioning of individuals with alcohol dependence syndrome revealed a significant improvement on the Frontal Assessment Battery, which “assesses conceptualization, mental flexibility, motor programming, sensitivity to interference, inhibitory control, and environmental autonomy” relative to a control condition (Gamito et al., 2014).

While no evaluations of mobile-based versions of commercially available “brain training” apps were found, research into the computerized versions of some training programs that offer mobile versions reveal unsubstantiated claims of efficacy (Redick et al., 2013; Shipstead, Hicks, & Engle, 2012; Simons et al., 2016). However, the popularity of these apps indicates a strong demand for more work in this area and supports tolerability and disseminability of this platform. For example, one such app, Lumosity, claims over 35 million app downloads (Lumosity, 2017). Thus, while the mobile platform may be tolerable to users, initial attempts at commercial mobile EF training may not have been conceived using evidence-based practices; thus, more research is warranted to optimize their efficacy.

Another indication of the promise of apps for EF training is the body of evidence supporting the feasibility and validity of *assessing* facets of EF via smartphones. For instance, several studies have found that neurocognitive assessments conducted via smartphone apps demonstrate high validity compared with gold standard measures and good test-retest validity (Brouillette et al., 2013; Schweitzer et al., 2016; Tong, Chignell, Tierney, & Lee, 2016; Wu et al., 2015), possibly indicating that at least certain facets of mobile phone-based EF training may map well onto established methods. However, assessment of EF skills fundamentally differs from EF training in many ways, and this growing focus within the field only speaks to an increasing appreciation of smartphone-based clinical tools within the broader EF domain.

Future Directions

In order to draw definitive conclusions about the relationship between training modality and potency, future studies implementing EF/AB trainings on mobile platforms should include direct comparisons to trainings delivered via personal computer. Additionally, the noted convenience and privacy of mobile technology indicates that future research should investigate trade-offs between the enhanced feasibility of smartphone-based administration and diminished effectiveness. For instance, it is possible the benefits of remote EF/AB training on a mobile platform (e.g., compliance, engagement) may outweigh the costs (e.g., distractibility, small screen size).

Gamification

EF/AB training protocols generally involve extremely (and deliberately) simple visual field and framework, such as pressing one of two computer keys in response to a single stimulus,

repeated several hundred times. The protocols can be “gamified” by including motivating feedback (e.g., sounds, graphics that indicate percent of the way complete), rewards for performance (points, badges, levels, special powers or privileges), and a unified story (with consistent actions, sounds, graphics, etc.; W. Boendermaker, Prins, & Wiers, 2013). Several gamified EF trainings have been developed thus far. For example, *Braingame Brian* is an inhibitory control and working memory training to reduce overeating in obese children (Verbeken, Braet, Goossens, & Van der Oord, 2013). The trainings are integrated into a game world (i.e., the inhibitory control training takes place within the village factory) and completing training segments rewards the player with extra powers and allows him to create inventions to help people in his village. Our research group has developed and is currently evaluating an inhibitory control plus evaluative conditioning training called *DietDash* that is framed within a supermarket environment. Players proceed quickly down supermarket aisles and decide whether to pull items into a shopping cart. Game elements include graphics, sound, points, badges and levels. *Shots* is an AB retraining game for problem drinking that uses the visual probe task (VPT; Van Schie & Boendermaker, 2014). Game elements include a slot machine-like graphical interface with spinning images, virtual coin rewards and level increases. In a related attention bias retraining game designed for Facebook called *Cheese Ninja*, the player controls a mouse running through a tunnel, and must grab pieces of cheese while avoiding cats (Boendermaker, Boffo, & Wiers, 2015). *CityBuilder* is a flexible game system with five training components (e.g., inhibition, attention, switching; W. Boendermaker et al., 2013) that can be switched on or off to suit the purpose of the training. In *CityBuilder*, more play earns the user the ability to add elements (trees, houses, roads) to a virtual city and to view others' cities.

Potential Advantages to Adherence and Efficacy

The tedium of repeated EF training bouts likely reduces adherence and thus potency. Using a boring task (or playing a boring game) in the hopes of achieving a longer-term goal requires the very executive control capacities that are postulated to be deficient. Using a gaming framework offers the possibility of creating a task that is inherently engaging and that an individual would be intrinsically motivated to complete over the long-term. If gamification increases adherence to repeated trainings it should also increase efficacy.

Potential Limitations

Creating gamified trainings requires resources and expertise, and involves the risks that the integrity of the cognitive training will be undermined, thus decreasing efficacy. Also, the reward elements of games could have unintended consequences such as undermining intrinsic motivation (Jaeggi et al. 2014; Deci et al. 1999; Boendermaker et al 2017). Reduced efficacy could also result if the gamified elements distract from the core training elements.

Empirical Evidence

A general systematic review of gamification of cognitive training indicated that gamification potentially increases engagement and motivation and reduces dropout, but that direct empirical evidence was lacking (Lumsden, Edwards, Lawrence, Coyle, & Munafò, 2016). Preliminary results of the *CityBuilder* trial suggest that participants find the game more enjoyable than a non-game version (W. Boendermaker et al., 2013). However, other games

have not been rated as fun, at least not for very long (Van Schie & Boendermaker, 2014; Verbeken et al., 2013). Of special note, some limited evidence exists to suggest that gaming elements do, in fact, increase enjoyment and adherence (Verbeken et al., 2013). In addition, preliminary results of the *CityBuilder* trial suggest that participants find the game more enjoyable than a non-game version (W. Boendermaker et al., 2013). However, other games have received lower enjoyment ratings, at least once participants have played repeatedly (Van Schie & Boendermaker, 2014; Verbeken et al., 2013). Of interest, adding a social game element has been shown to increase motivation and user experience (Boendermaker, Prins, & Wiers, 2015).

The body of empirical evidence evaluating the efficacy of gamified eating-related EF/AB training is extremely limited. The non-eating-specific systematic review mentioned above gamification of cognitive training noted several studies reporting that gamification increases engagement and motivation and reduces dropout, and also obtained evidence that gamification enhances the effectiveness of the training (Lumsden et al., 2016). However, this review also identified numerous methodologic problems in these studies, limiting the confidence of any conclusions. In one of the few studies of gamified cognitive training and eating/drinking behavior, children who played 25 sessions of *Braingame Brian* over six weeks showed more EF and weight maintenance benefits than children randomized to a usual care control (Verbeken et al., 2013). Boendermaker et al. (2015) directly compared gamified cognitive bias modification (*Cheese Ninja Game*) to standard training. While the game was effective, it did not provide additional efficacy relative to standard cognitive bias modification training.

Future Directions

Future research could explore a number of the issues just discussed. Most fundamentally, future work is needed to ascertain the extent to which gamifying EF interventions and ABM increases engagement and adherence, and which elements of gamification maximize adherence. For example, designs could compare a non-gamified EF training to a superficially modified training to a full game immersion training. At the same time, future research should determine how gamification-related modification of standardized EF training paradigms detract from, or perhaps even enhance, the potency of the training.

Virtual Reality

Virtual reality (VR) presents a simulated natural environment, usually through a lifelike interactive three-dimensional space that responds realistically to head movement (Pugnetti et al., 1998). VR's realism and immersion is theorized to enhance assessment validity, intervention fidelity and engagement, and enactment of skills (Sullivan et al., 2013). Specifically, VR technology is able to create high degrees of immersion, or “presence” in a simulated scenario, which promotes better generalizability of training to the real world (Powers & Emmelkamp, 2008) and is associated with improved treatment outcomes (Hoffman, 2004; Regenbrecht, Schubert, & Friedmann, 1998; Slater, Pertaub, & Steed, 1999).

Potential Advantages for Efficacy and Adherence

VR offers distinct advantages over traditional treatment approaches, which could improve the effectiveness of EF/AB training. First, VR creates environments with a degree of realism that is impossible using other techniques, thus allowing individuals to practice skills that are directly transferrable to everyday behaviors (Lee et al., 2003), while allowing the researcher to maintain control over the situation (Hone-Blanchet, Wensing, & Fecteau, 2014). For example, Zhang and colleagues developed an immersive VR kitchen environment for patients with traumatic brain injury (TBI) undergoing rehabilitation in which patients completed a multi-step meal preparation task. Performance in the virtual kitchen was positively correlated with performance in an actual kitchen. These results demonstrate that behaviors learned in a VR task can be directly translated to real-world situations (Zhang et al., 2003), a finding that has been similarly demonstrated in several other studies (Kenyon & Afenya, 1995; Rose, Attree, Brooks, Parslow, & Penn, 2000; Witmer, Bailey, Knerr, & Parsons, 1996). VR environments are also flexible and can be easily altered by the researcher, which allows trainings to be tailored to individual skill deficits (Bordnick, Carter, & Traylor, 2011). Given their ability to replicate real-world environments that are directly relevant to an individual's specific training needs, VR-based trainings have the potential to increase generalizability and thus the effectiveness of EF/AB trainings.

Second, VR is especially helpful for training behavior in situations that are difficult or impossible to replicate in the clinic (Powers & Emmelkamp, 2008). As such, VR may be especially helpful in closing the gap between the analog of the training paradigm and the reality of acquisition and consumption of food and drink as it occurs in the daily environment. Furthermore, VR environments are able to recreate more complex contextual cues that may contribute to behaviors (e.g., social pressure at a party) rather than simple two-dimensional images, which can further the training's realism and generalizability (Bordnick et al., 2011).

Finally, VR-based trainings are capable of producing high levels of immersion in a lifelike environment. Greater levels of immersion, or “presence” can improve adherence by increasing the degree of engagement with treatment, and has been shown to be associated with reduced drop-out (Krijn et al., 2004). Given their ability to create virtual worlds that closely resemble an individual's everyday environment and create high levels of immersion, for example, by creating a highly realistic grocery store environment in which the individual practices inhibiting a “go” response to palatable foods, VR-based trainings are likely to be more successful in achieving high adherence rates and generalizability, and thus superior behavior change.

Potential Limitations

Despite the realism of VR trainings, obvious differences remain between VR training paradigms and the real-world environment (e.g., the quality, and thus realism, of VR images may vary, the behavioral mechanics of eating may be missing or altered, and there is no possibility of actual pleasure from choosing a palatable food). In addition, implementing VR trainings requires a range of equipment, which can be costly, including head mounted display to provide wraparound visual scenes, noise cancelling headphones, tracking devices

for coordinating individual's movement through the virtual world, and systems to provide sensory stimuli (e.g., scent machines, tactile stimuli), and technological expertise is required to program and set-up VR paradigms (Bordnick et al., 2011). Furthermore, some individuals experience sensations of nausea or vertigo during or after VR exposure (i.e., "cybersickness; De Leo, Diggs, Radici, & Mastaglio, 2014). Cybersickness (i.e., nausea caused by the discrepancy between actual and perceived motion) has the potential to lead to failure to fully engage in VR trainings or drop out of a training protocol early to due intolerable physical effects.

Empirical Evidence

No direct evidence exists that VR enhances efficacy (or adherence) of EF/AF trainings. However, a set of related findings suggest that this technology holds promise for EF/AF eating-related training. For example, VR has successfully been used in treatment of anxiety disorders (Powers & Emmelkamp, 2008), pain management (Hoffman, 2004; Mahrer & Gold, 2009), and for a variety of neurocognitive assessments, including assessment of planning difficulties in older adults, impairments in activities of daily living (ADLs), and executive functioning deficits post-stroke (Laver, George, Thomas, Deutsch, & Crotty, 2012; Lee et al., 2003; McGeorge et al., 2001; Pugnetti et al., 1998; Rand, Weiss, & Katz, 2009). VR-based neurocognitive rehabilitation for conditions like schizophrenia and ADHD has also been delivered (da Costa & de Carvalho, 2004; Lee et al., 2003).

In the realm of weight loss, VR has been used to improve body image among obese participants (Riva, Bacchetta, Baruffi, & Molinari, 2001) and individuals with binge eating disorder (Cesa et al., 2013), decrease body disturbances among bariatric surgery patients (Wiederhold & Riva, 2012), assess attention-bias towards high-calorie food (Schroeder, Lohmann, Butz, & Plewnia, 2016), and enhance weight maintenance and the practice of new weight management skills (Coons, Roehrig, & Spring, 2011; Sullivan et al., 2013). Several studies have also investigated the use of VR to provoke food (Ferrer-García, Gutiérrez-Maldonado, & Pla, 2012; Ledoux, Nguyen, Bakos-Block, & Bordnick, 2013), and alcohol cravings (Bordnick et al., 2008; Ryan, Kreiner, Chapman, & Stark-Wroblewski, 2010; Traylor, Bordnick, & Carter, 2009).

Evidence from studies comparing VR stimuli with real or photographed stimuli supports the ecological validity of VR technology. For example, in a sample of individuals with eating disorders, exposure to real food and VR food stimuli produced equivalently high physiological stress responses compared to two-dimensional photographs of the same food (Gorini, Griez, Petrova, & Riva, 2010). Similarly, in a study on nicotine craving, Lee et al, 2003, found that a VR environment, compared to two-dimensional photographs, induced significantly greater nicotine cravings. While research in this field is still emerging, VR appears to hold considerable benefits in terms of ecological validity.

Future Directions

Overall, VR technology holds great promise in the realm of eating behavior and weight loss. Given that VR has been successfully applied in the fields of neurocognitive assessment and weight control, it could be a tool to meaningfully enhance the impact of computerized

EF/AF trainings on eating behavior by constructing trainings with more realistic stimuli to enhance the potency and generalizability of the training task. Moreover, VR-based EF/AF trainings have advantages in that they train the same basic cognitive functions being utilized and deployed in real-world food choice scenarios, and thus are directly transferrable to these situations. As mentioned, there is no existing research on the efficacy of VR-based EF/ABM trainings to improve regulatory control of appetite eating and drinking behaviors. As such, research is needed to examine whether VR-based trainings do in fact increase effectiveness of trainings due to greater generalizability and increased engagement in, and thus adherence to, treatment. Overall, despite some of the potential limitations noted above, VR holds considerable promise for improving upon the current modes of delivery of EF trainings, and future research should empirically evaluate the effectiveness of VR-based training delivery for eating and drinking behaviors specifically.

Personalization

Another recent innovation in EF/AB training paradigms in particular has been to match food and drink stimuli with trainee preferences. Studies have found that training no-go to specific foods does not generalize to other palatable foods (Chen, Veling, Dijksterhuis, & Holland, 2016; Houben & Jansen, 2011; Lawrence, Verbruggen, Morrison, Adams, & Chambers, 2015), and that training no-go to specific foods, e.g., licorice candy (Veling, Aarts, & Papies, 2011) and chocolate (Houben & Jansen, 2011), reduces intake of those foods, in particular. As people vary in their preferences for types of unhealthy foods (e.g., sweet versus salty snacks), specific unhealthy foods (e.g., soda versus sweet tea), and even brand (e.g., Coca-Cola versus Pepsi), researchers have begun to examine whether matching food stimuli to trainee preferences (i.e., personalizing stimuli) increases training efficacy.

Potential Advantages to Adherence and Efficacy

The neurocognitive process being trained (e.g., inhibitory control) ought to be more powerfully attached to the desired food (e.g., Coca-Cola) if the stimuli used to train that process resembles the food. In addition, using images of foods a trainee prefers and likely sees often is expected to increase training efficacy by optimizing stimuli salience and motivation reward. Evidence suggests that food-specific inhibitory control trainings modify motor responses, change the reward value of food, modify attention to food, and/or induce rule based learning (see for review: (Stice, Lawrence, Kemps, & Veling, 2016; Veling, Lawrence, Chen, van Koningsbruggen, & Holland, 2017), and these mechanisms depend on the salience, personal relevance, and/or motivation reward related to the stimuli (i.e., greater salience, relevance, and motivation reward are more likely to produce changes in food-related inhibitory control and eating behavior (Bartholdy, Dalton, O'Daly, Campbell, & Schmidt, 2016; Schonberg et al., 2014). Finally, personal relevance of stimuli may increase participant interest, attention, and motivation to complete training, thereby increasing adherence with a high-frequency training prescription. Indeed, studies have found that inhibitory control training effects are stronger when the training stimuli produced a stronger motor impulse in participants at baseline (Veling et al., 2011) and had the highest subjective palatability ratings by trainees at baseline (Schonberg et al., 2014). Thus, training stimuli

should be selected so as to maximize salience and relevance to the trainee, which is expected to increase adherence and efficacy in terms of both inhibitory control and behavior transfer.

Potential Limitations

One challenge in personalizing training stimuli is that the optimal level of personalization specificity is unknown. For example, a trainee might report preferring chocolate cake to other types of cakes or sweets, but visual representations of chocolate cake can vary widely by category (e.g., extravagant cake from bakery versus simpler homemade cake), absolute size (three layer versus single layer), portion size (whole cake or slice, size of slice), packaging (boxed cake versus snack cake), and brands. If training efficacy depends on stimuli salience and personal relevance, more detailed information about the brand, portion, and packaging of preferred food items may be warranted. Conversely, making training stimuli too specific (i.e., training only to those foods most often consumed) may have perverse effects on weight loss if trainees begin to substitute other palatable high-calorie foods for their preferred training foods (e.g., eating ice cream in place of chocolate cake; salty snacks in place of sweets). Further, the technical ability to match training stimuli to trainee preferences or reported dietary intake requires additional programming skills, time, and development burden for research teams, which may decrease feasibility. Finally, the ability to compare training effects across participants is also limited because training stimuli are not standardized.

Empirical Evidence

Only one published study to date has matched EF or AB training food stimuli to participant preferences. In this pilot study, Stice et al. (2016) used a food response inhibition training which included a stop-signal task, go/no-go task, dot-probe response-facilitation training, respond-signal training, and visual search. Both high-calorie and low-calorie training images were matched to participant preferences. Adherence to four 50-minute weekly trainings delivered in the laboratory was 100% (Stice et al., 2016). Because Stice, et al. (2016) did not measure intake of training foods as an outcome, evidence for the relative increase in efficacy from personalizing stimuli remains weak; however, participants in the training condition showed greater reductions in percent body fat at post-training and 6-month follow-up than those in the control condition. Studies examining food-specific inhibitory control training without personalization did not report on adherence because trainings were conducted in the laboratory rather than remotely, with the exception of (Lawrence, O'Sullivan, et al., 2015), which found 82% adherence to four 10-minute remotely delivered IC trainings when compliance was not encouraged.

Future Directions

While evidence suggests stimuli personalization would enhance adherence and training efficacy, only one published study (i.e., Stice et al., 2016) has examined this question empirically and its published outcomes did not include objective measurement of dietary intake. Notably, to our knowledge, only one study has examined changes in eating behavior outside the laboratory following inhibitory control training to specific (but not personalized) foods (Veling et al., 2011), rather than consumption in a laboratory setting. Future studies should aim to match training stimuli to participant preferences, conduct remote trainings,

and examine consumption of both training and non-training foods in a naturalistic setting as an outcome. Relatedly, while targeted inhibitory control training has been shown to successfully decrease consumption of specific foods in the laboratory post-training (i.e., inhibitory control training for chocolate reduced chocolate consumption in high-trait chocolate cravers in Houben & Jansen, 2011), evidence is lacking for the long-term efficacy of food-specific trainings. Future studies should include follow-up assessments to examine EF/AB, dietary intake, and weight at longer intervals post-training.

Two ongoing projects have piloted matching training stimuli to trainees' reported preferences and objectively measured dietary intake. The University of Exeter Food T App (Lawrence, 2017) allows the user to select which foods he or she regularly consumes and thus wishes to train to resist. The Drexel University DietDASH program uses objectively measured dietary intake (a food frequency questionnaire and ASA24 24-hour dietary recalls) to generate training stimuli based on the high-sugar foods contributing the most sugar to the trainee's diet. The stimuli selection algorithm in the DietDASH study anticipates categorical substitutions, such that participants are presented with images of high-sugar items similar to those they endorse eating most often. Outcome measures in this study include food-specific IC, dietary intake, and weight, measured at post-training and 4 weeks post-training.

Another promising but unstudied aspect of personalization includes matching EF or ABM training type to participant deficits. Though obesity is related to poorer neurocognitive performance generally (Cournot et al., 2006; Fagundo et al., 2012; Gunstad, Paul, Cohen, Tate, & Gordon, 2006), and studies have found greater inhibitory control deficits in overweight and obese adults compared to healthy controls (Houben, Nederkoorn, & Jansen, 2014; Mole et al., 2015), others have found no significant differences in inhibitory control when measured using SSTs (Chamberlain, Derbyshire, Leppink, & Grant, 2015; Grant, Derbyshire, Leppink, & Chamberlain, 2015; Hendrick, Luo, Zhang, & Li, 2012; Lawyer, Boomhower, & Rasmussen, 2015; Nederkoorn, 2014; Nederkoorn, Smulders, Havermans, Roefs, & Jansen, 2006). Mixed findings may be attributed to individual differences in specific neurocognitive deficits (e.g., inhibitory control versus working memory). Further, response-inhibition training against high-calorie foods has shown greater effects in participants with elevated impulsivity (Houben & Jansen, 2011), suggesting that training efficacy might be optimized by matching the training type with participant deficit. An ideal training paradigm could use an assessment of EF and ABM domains (e.g., inhibitory control, working memory, attention, cognitive flexibility, set shifting, planning) followed by an automatically-constructed tailored training regimen based on those deficits.

Conclusion

While executive function and attention bias trainings for eating-related behavior show initial promise, several challenges remain, including engagement with and adherence to the trainings in the long term, and overall potency of the training, especially in terms of real-world eating behaviors. As described above, remote training, training via smartphone, gamification, virtual reality, and personalization all represent promising innovations in EF/AB training of eating-related behavior. In particular, these innovations may represent ways to increase engagement and adherence to tasks that are typically repetitive, boring, and

only available in the laboratory, which could, in turn, increase efficacy. Disadvantages to some of these innovations, such as problems with technology adoption and cost of development (e.g., VR, gamified versions of tasks) should be addressed and weighed against the potential benefits of potentially increased adherence and efficacy. More research examining the incremental benefit (e.g., comparing to standard versions) of these innovations on standard EF/AB trainings is necessary to understand if such investment is worth the cost. While empirical evidence precludes conclusion of which innovation may be the most promising venue to increase efficacy and adherence of EF/AB trainings, it is possible that combinations of the innovations described above could be especially potent. For example, at-home and smartphone-based trainings with gamified elements could combine the advantages of remote training (e.g., participants can complete on their own time) with those of gamification (e.g., increased engagement and motivation) to lead to an especially strong EF/AB training.

In addition, it is unlikely that EF/AB trainings in and of themselves would be powerful enough to induce comparative weight loss/maintenance to gold standard behavioral interventions. As such, integrating EF/AB trainings with known effective interventions for eating-related behavior change (e.g., behavioral weight loss treatments) is a necessary future avenue for research. Although a great deal more empirical work is necessary, the technological innovations described above are likely to be part of the ongoing effort to improve the potency of EF/AB training for appetitive behaviors.

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Table 1
Summary of Technological Innovations in EF Training for Eating/Drinking Behavior

Category	Relevant Empirical Studies	Potential Advantages		Potential Limitations	Empirical Evidence	Future Directions
		Adherence	Efficacy			
Home/ remote training	Houben, Wiers, & Jansen, 2011; Wiers et al., 2015; Forman et al., 2016; Lawrence et al., 2015; Veling, van Koningsbruggen, Aarts, & Stroebe, 2014; Houben, Dassen, & Jansen, 2016; Boutelle, Montreal, Strong, & Amir, 2016	Increase ease of repeated training which improves adherence	Increased ease creates possibility for longer duration of trainings of similar quality to in-lab trainings	Compliance requires buy-in to training rationale and high levels of motivation	Produce clinically meaningful behavior changes immediately following training and during short follow-up periods (e.g., 3 months).	Comparative trials to assess feasibility, acceptability, and effectiveness of home vs. in-lab trainings; Investigate factors related to nonadherence with remote trainings
Smartphone	Blackburne, Rodriguez, & Johnstone, 2016a;	No clear data related to food-specific EF training	Smartphones are ubiquitous, additional means of sensory feedback	Increased distractibility, screen size may affect training efficacy	Promising, but only based on one study	Comparative trials with adequate control groups (e.g., computerized training versus phone training)
Gamification	Van Schie & Boendermaker, 2014; Boendermaker et al. (2013); Boendermaker, Boffo, Wiers (2015); Verbeken et al. (2013)	Gamification elements increase engagement and interest; reduce boredom	Improved compliance may lead to improved efficacy	Gamification requires specialized resources and expertise; reductions in integrity of the cognitive training; distraction from competing stimuli	Very few direct tests of efficacy; some evidence to suggest gamified versions are efficacious but no evidence they are superior to standard training	Research investigating extent to which gamifying EF interventions increases engagement and adherence; which elements of gamification maximize adherence; how gamification-related modification of standardized EF training paradigms affect potency of the training.
VR	None directly relevant to EF trainings for behavior change	High degree of realism and ability to recreate scenarios that are normally difficult to replicate in the clinic may allow for greater transfer to real world	Produces greater 'presence' and treatment engagement which may result in improved adherence	Need for proper equipment; potential for higher cost than more simple modes of delivery (due to equipment); cybersickness	Promising, able to create realistic scenarios and induce cravings; no direct investigations of effects on eating/drinking behavior change	Trials of VR-based EF trainings for eating/drinking behavior to evaluate effect on behavior change, engagement in treatment
Personalization	Stice, Lawrence, Kemps, Veling (2016)	May increase participant interest, attention, and motivation, consequently increasing adherence	Enhances stimuli salience, relevance, and motivation reward to participant which is likely to increase efficacy of IC training	Optimal level of training stimuli specificity unknown; additional programming skill, time and development; non-standardization of stimuli across participants	Single pilot study data available; 100% adherence to four 50-minute trainings; no direct investigation of changes in eating behavior following personalization	Trials comparing effects of personalized and general (non-personalized palatable) food-specific EF training on eating behavior in naturalistic setting