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Mechanisms of Change in a Go/No-Go Training Game for Young Adult Smokers

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Objective: Smoking is a major cause of worldwide morbidity and mortality. Evidence-based intervention programs to help young adults quit smoking are largely lacking; identifying targets for intervention is therefore critical. A candidate target is inhibitory control, with previous studies on Go/No-Go trainings showing behavior change in the food and alcohol domain. The current study examined the mechanisms of change of *HitnRun*, a Go/No-Go game, in a smoking population that was motivated to quit. ***Method:*** A 2-armed experimental study (n = 106) was conducted and young adults (M_{age} = 22.15; SD_{age} = 2.59) were randomly assigned to either play *HitnRun* or to read a psychoeducational brochure. Prior to and directly following the intervention period, smoking-specific and general inhibitory control, perceived attractiveness of smoking pictures, and weekly smoking behavior were assessed. ***Results:*** Results indicated that Go/No-Go training seems to decrease evaluations of smoking stimuli rather than top-down smoking-specific and general control processes. Similar reductions for weekly smoking were found in both groups. ***Conclusions:*** Go/No-Go training did not differentially influence smoking-specific inhibitory control, general inhibitory control and weekly smoking behavior. Go/No-Go training might be able to decrease evaluations of smoking stimuli, yet based on the current study we cannot rule out the possibility of regression to the mean. More research and iterative design is needed to better understand the potential role of Go/No-Go training in smoking cessation interventions, as well as exploring other evidence-based mechanisms (e.g., peer processes, self-efficacy) that might be an important addition to smoking cessation interventions for young people.

Keywords: Go/No-Go training, smoking cessation, games, mechanisms of change, trans-diagnostic process

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Smoking is one of the leading public health problems in the world, each year killing about 20,000 people in the Netherlands alone (Volksgezondheidenzorg Info, 2016), and about six million people worldwide (World Health Organization, 2016). Despite the number of Dutch smokers under 16 years decreasing, the number of older adolescent and young adult smokers between the ages of 16 and 25 has shown a small increase (Centraal Bureau Voor de Statistiek, 2017). It is therefore critical to invest in interventions to help these at-risk youth and young adults quit smoking. A recent review on smoking cessation interventions specifically for youth and young adults demonstrated that there is not enough evidence to recommend one specific intervention model for this at-risk group (Fanshawe et al., 2017). The limited evidence available seems to suggest that complex interventions that address a variety of mechanisms related to smoking among youth and young adults are most promising (Fanshawe et al., 2017; Gabble et al., 2015). However, it is often not clear which exact mechanism(s) drive observed effects (Fanshawe et al., 2017; Gabble et al., 2015). Therefore translation of basic science into clinical practice is necessary. Consequently, the goal of the current study was to find and test a promising mechanism of change that can eventually contribute to smoking cessation in youth.

Inhibitory Control

One crucial determinant for the onset and maintenance of smoking among youth and young adults is inhibitory control, with the

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developmental period of adolescence particularly characterized by lower inhibitory control (Luna et al., 2010). *Inhibitory control* refers to the ability to adaptively suppress or stop behavior when necessary (Smith et al., 2014). The inability to quit smoking regardless of negative consequences may be the result of deficits in inhibitory control (Field & Cox, 2008). A Go/No-Go (GNG) task, in which participants have to press a button when a Go cue is shown and have to withhold that response when a No-Go cue is presented, is commonly used to measure inhibitory control. Several studies have shown that adolescents and young adults who smoke more often have poorer control over their impulses on such a GNG task than those who do not smoke (specifically in youth: Yin et al., 2016; meta-analysis including young adults and adults: Smith et al., 2014;). Moreover, deficits in inhibitory control capacity are also observed among other substance-dependent individuals (e.g., cocaine, MDMA) or individuals with behavioral addictions (e.g., food, Internet addiction; Lavagnino et al., 2016; Smith et al., 2014). This has led to the hypothesis that inhibitory control could be conceptualized as a trans-diagnostic process, that is, a common factor behind the development and maintenance of substance dependence and behavioral addictions (Bickel et al., 2015). Consequently, intervening in such a trans-diagnostic process could be very promising since manipulating inhibitory control capacity might affect multiple health behaviors and disorders.

In the last decade, there has been increasing attention for procedures aimed at training inhibitory control, which is mainly done using a modified version of the GNG task. Participants are trained to respond immediately to a neutral stimulus, but inhibit or stop their response when a motivational stimulus (food or substance of interest) is presented (Lawrence et al., 2015). So far, three meta-analyses have shown significant effects of GNG training on alcohol or food intake, with medium effect sizes (Allom et al., 2016; Jones et al., 2016; Turton et al., 2016). Thus, GNG training seems to facilitate behavior change for the specific motivational stimulus trained, at least in the short term and perhaps in the long term (Allom et al., 2016; Jones et al., 2016).

To our knowledge, only two studies have tested smoking-specific GNG training among young adult and adult smokers (Adams et al., 2017; Bos et al., 2019). In the study by Adams et al., GNG training among smokers did not strengthen smoking-specific top-down inhibitory control or decrease cigarette use. However, there was weak evidence that GNG training may have enhanced the ability to resist smoking. The study by Bos et al. showed no effects of GNG training on daily cigarette consumption or smoking abstinence. Although the results from these studies were not so positive, it is too soon to reject GNG training as a possible target of intervention. In both studies, issues such as power, dose, and nonspecific factors might have played a role in disguising actual training effects. Additionally, Adams et al. only included a measure of top-down inhibitory control to measure the effects of the GNG training, and Bos and colleagues did not include any measure to test for proximal effects of GNG training. It is commonly assumed that a GNG training reinforces a top-down executive control process, thereby directly increasing capacity to resist impulses toward the behavior one wants to reduce (e.g., Andrés, 2003). However, recently researchers have argued that other mechanisms may be responsible for the effects on food- and alcohol intake (Veling et al., 2017).

Alternative Explanations for Behavioral Effects of GNG Training

In a recent review by Veling et al. (2017), two additional explanations for the effects of GNG training beyond top-down processes were discussed. First, learning bottom-up stimulus-stop associations is an alternative explanation for the effects on food- and alcohol intake (Verbruggen et al., 2014). It may be that the consistent mapping of stimuli onto either stopping or going in a motivational stimulus specific GNG training fosters the development of automatic inhibition through stimulus-stop associations (e.g., Stice et al., 2016; Verbruggen & Logan, 2008). Initially GNG training may actively recruit top-down inhibitory control to withhold responses to No-Go stimuli, but this top-down control may diminish over time once direct bottom-up stimulus-stop associations have been acquired (Verbruggen et al., 2014). These stimulus-stop associations could be seen as equivalent to a learned reflex. We did not test the bottom-up account as there is no established method at this point to reliably disentangle this second mechanism from the other two accounts (Veling et al., 2017).

The third explanation, the behavior stimulus interaction (BSI) theory, proposes that GNG training decreases perceived attractiveness of No-Go stimuli (Chen et al., 2016; Veling et al., 2008, 2017). When the perceived attractiveness of motivational stimuli is lower, impulses toward these stimuli may be weakened, making individuals less prone to approach this motivational stimulus and increasingly able to inhibit this response (Veling et al., 2008, 2014). Specifically, reduction through inhibition is argued to be specific to stimuli inherently associated with an approach orientation. In line with this reasoning, training should result in a larger subjective decrease in attractiveness of appetitive No-Go stimuli than Go or neutral or untrained No-Go stimuli (i.e., devaluation effect).

The devaluation explanation has garnered the most evidence so far with several studies showing devaluation of attractive stimuli after repeated pairing with No-Go cues as measured with visual analogue scales (e.g., Chen et al., 2016, 2017; Lawrence et al., 2015; Veling et al., 2008; but see Jones et al., 2016, suggesting less robust findings when indirect measures of evaluation are used). However, these alternative explanations have not been tested very often and therefore it is yet impossible to make inferences about the mechanisms at work (Veling et al., 2017). The current study aimed to examine two of the potential underlying mechanisms (i.e., top-down and devaluation account) of the GNG training. Furthermore, it is currently unknown whether or not smoking-specific GNG training effects generalize to general inhibitory control capacity (no motivational stimuli in the task; Berkman et al., 2012; Blackburne et al., 2016; Bos et al., 2019). Therefore, we also included an Stop Signal Task to test potential transfer of GNG training effects to general inhibitory control.

Barriers to Implementation and Evaluation of Interventions

In addition to mechanisms of change, there are practical issues including accessibility and engagement that have an impact on intervention effectiveness and implementation in clinical practice (Backinger et al., 2007; Fanshawe et al., 2017; Sussman & Sun, 2009), and we argue that games can address these limitations. We previously provided two detailed empirical reviews (Granic et al., 2014; Scholten & Granic, 2019) that support the rationale for using digital games as intervention tools for young people. In short, well-designed applied games are intrinsically motivating, offer a strong sense of agency, are simply fun, and can overcome the stigma associated with traditional and self-help interventions. They also provide a compelling virtual playground to not only gain knowledge, but also practice skills. We included a more detailed explanation of the barriers to implementation and evaluation of interventions in the online supplemental materials.

Design and Hypotheses

In the present study, we examined the effects of *HitnRun*, a game based on principles of GNG training, in young adult smokers who are motivated to quit smoking. An psychoeducational brochure "What you should know about quitting smoking" (Trimbos Instituut, 2014) was selected as the active control intervention. This is a common intervention for smoking cessation that does not include any inhibitory control training components (Boot et al., 2013). To better understand how GNG training impacts on behavior, we examined potential mechanisms of change and insured the study was appropriately powered. Finally, we also explored the effects of GNG training on smoking behavior, since ultimately the mechanisms of change we tested should have an effect on smoking behavior.

Based on the theoretical assumptions regarding GNG training discussed above, we tested four hypotheses: (a) we expected that young adults who played the game would show more smoking-specific inhibitory control at posttest than the participants in the brochure group. (b) We had no specific hypothesis whether smoking-specific training effects would transfer to general inhibitory control. Because of readability and length reasons, we shortly discuss the results regarding this measure in the main article; an extensive discussion can be found in the online supplemental materials. (c) Based on the BSI theory, we expected decreased subjective attractiveness ratings for smoking stimuli at posttest in the game group (i.e., devaluation effect), relative to the brochure group. (d) We did not expect differences in weekly smoking behavior between intervention groups, mainly because smoking cessation among youth is a difficult, multideterminant problem and more comprehensive interventions are considered necessary for effectiveness. This study was purposely set up, and powered accordingly, to examine potential underlying mechanisms of change of a game-based GNG training (i.e., top-down inhibitory control and devaluation), and therefore not yet for smoking cessation.

Materials and Method

Participants

Young adults were recruited through online advertisements and flyers spread around the Radboud University campus. For practical reasons of recruitment and consent, we only included young adults older than 18 years in our study. When young adults were interested in participation, they were screened for smoking behavior and motivation to quit smoking. Inclusion criteria were (a) aged 18–30 years, (b) at least a weekly smoker, (c) motivated to quit smoking for at least five weeks during study participation (Prochaska et al., 1994), and (d) signed informed consent. Exclusion criteria included (a) taking psychotropic drugs and (b) receiving psychosocial care. Young adults who were eligible were invited to participate in the study. Target sample size was set at 98 participants, based on a priori power analysis using G*Power 3 (Faul et al., 2007; repeated-measures analysis of variance [RM-ANOVA], between subjects design; η^2 = .06, α = .05, power = .80). In total, 106 young adults (54.7% females) were enrolled in the study with a mean age of 22 (M_{age} = 22.15; SD_{age} = 2.59), allowing for 5–10% attrition (see Table 1 for all participant characteristics).

Procedure

Data were collected at the Behavioural Science Institute Laboratory of the Radboud University. Participants were asked to refrain from smoking at least one hour before the start of the first lab visit (i.e., pretest). This moment was also the official start of the intervention period of five weeks in which participants tried to quit smoking. At the first lab visit, participants provided informed consent and were randomized into either the game group (n = 54) or the brochure group (n = 52). Randomization was performed by an independent researcher using random number generation and was stratified by sex. Test procedures lasted approximately 90 min including (in order of assessment): general inhibitory control, weekly smoking behavior by means of questionnaires, expectations of effectiveness for both interventions, smoking-specific inhibitory control, and smoking and neutral picture evaluation. Subsequently, participants received an explanation of the intervention they were randomly assigned to. Participants in the brochure group were instructed to read the brochure at least once at home during the intervention period and were reminded halfway through the intervention period to engage with the intervention via a personalized e-mail. Participants in the game group were instructed to play the game at least once per week for 10 min and received a personalized e-mail each week to keep them engaged with the intervention. They practiced playing the game once in the lab.

Participants were allowed to use other smoking cessation aids to help them stay abstinent during their quit attempt; we asked them to report on these aids at posttest. Five participants reported to have used other aids during their quit attempt, ranging from food-related replacements (nonnicotine containing chewing gum; n = 1), other self-help materials (n = 1), or nicotine replacement aids (e-cigarette, nicotine patches, and nicotine gum; n = 3).[1] After the 5-week intervention period, participants came to the lab for the second time (i.e., posttest) and completed the same procedure as at pretest. At the end of the second lab visit, participants received course credit or a €50 gift certificate for their participation. The current study was approved by the ethics committee of the Faculty of Social Sciences at Radboud University (ECSW2015-2206-318) and registered at the Dutch trial Register (No. NTR5680).

[1] We re-ran our weekly smoking analyses without the five participants that reported to use additional aids to quit smoking. These results did not differ from the results over the whole sample, nor did the additional use of smoking cessation aids moderate the effect of group on smoking outcomes. Therefore, we did not covary for the use of additional smoking cessation aids.

Table 1
Participant Characteristics and Outcome Variables per Group at Pretest

Characteristic	Brochure group	Game group	Test statistic (*t*-test or χ^2 test)
Sex, *n* (%)			
Male	22 (42.3%)	26 (48.1%)	
Female	30 (57.7%)	28 (51.9%)	χ^2 (1, *n* = 106) = .37, *p* = .546
Age, *M* (*SD*)	22.52 (2.63)	21.80 (2.53)	*t*(104) = 1.44; *p* = .152
Education level, *n* (%)			
Preparatory higher general education (i.e., Havo)	6 (11.5%)	9 (16.7%)	
Preuniversity education (i.e., VWO)	21 (40.4%)	21 (38.9%)	
Vocational education (i.e., MBO)	7 (13.5%)	4 (7.4%)	
Higher general education (i.e., HBO	6 (11.5%)	8 (14.8%)	
University education (i.e., WO)	12 (23.1%)	12 (22.2%)	χ^2 (4, *n* = 106) = 1.67, *p* = .797
Game experience, *M* (*SD*)	5.72 (10.81)	4.00 (5.87)	*t*(104) = 1.02; *p* = .308
Years of smoking, *M* (*SD*)	5.64 (3.31)	5.11 (2.17)	*t*(90.21) = .73; *p* = .470
Nicotine dependence, *M* (*SD*)	2.15 (1.95)	2.31 (1.91)	*t*(104) = −.43; *p* = .669
Cigarettes a week, *M* (*SD*)	57.21 (43.44)	55.62 (38.52)	*t*(103) = .20; *p* = .843
Motivation for change, *n* (%)			
Not at all	0 (0%)	1 (1.9%)	
A little bit	0 (0%)	2 (3.7%)	
Neutral	7 (13.5%)	6 (11.1%)	
Much	28 (53.8%)	21 (38.9%)	
Very much	17 (32.7%)	23 (42.6%)	χ^2 (4, *n* = 105) = 4.97, *p* = .291
Expectations, *M* (*SD*)	14.38 (3.83)	9.56 (5.33)	*t*(96.22) = 5.37; *p* < .001
No-Go accuracy, *M* (*SD*)			
Smoking pictures	.71 (.13)	.67 (.18)	*t*(94.31) = 1.50; *p* = .136
Neutral pictures	.71 (.14)	.67 (.18)	*t*(100.45) = 1.29; *p* = .200
Go reaction time (ms), *M* (*SD*)			
Smoking pictures	270.75 (38.74)	269.06 (38.68)	*t*(104) = 1.59; *p* = .116
Neutral pictures	282.67 (46.05)	281.12 (41.49)	*t*(104) = 1.45; *p* = .152
SSRT (ms), *M* (*SD*)	.27 (.05)	.27 (.05)	*t*(103) = −.17; *p* = .868
Evaluation scores, *M* (*SD*)			
Untrained smoking pictures	−14.10 (27.59)	−18.37 (30.36)	*t*(104) = .76; *p* = .450
Untrained neutral pictures	13.63 (8.27)	14.13 (14.15)	*t*(86.03) = −.22; *p* = .826

Note. Havo = hoger algemeen vormend onderwijs; VWO = voorbereidend wetenschappelijk onderwijs; MBO = middelbaar beroepsonderwijs; HBO = hoger beroepsonderwijs; WO = wetenschappelijk onderwijs; SSRT = Stop Signal reaction times.

Interventions

Game

Here we discuss the basic mechanics of the endless runner game *HitnRun* (Poppelaars et al., 2018). Full details can be found in the online supplemental materials. The endless runner game *HitnRun*, based on principles of GNG training (Lawrence et al., 2015; Veling et al., 2014), was codesigned with the Games for Emotional and Mental Health Lab and Embodied Games LLC. In endless runner games, players control an avatar that is running forward continuously while collecting points along the way by moving the character up-and-down or left-to-right (Parkin, 2013). We selected the endless runner genre for two reasons: (a) commercially available endless runners are extremely popular (e.g., Temple Run; Parkin, 2013); (b) endless runners require continuous accurate and quick responding, and therefore they are particularly well-matched for GNG training.

HitnRun is a PC game (Figure S1 in online supplemental materials), taking place in a city filled with billboards on which pictorial stimuli are shown for 1,000 ms. Stimuli consisted of pictures with neutral content (120 pictures) and smoking content (40 pictures). Players were instructed to press the spacebar as fast and accurately as possible in order to jump through billboards (Go trial) or to withhold their response (No-Go trial) based on billboard border color. Go and No-Go borders were blue and yellow respectively and appeared 100 ms after stimuli onset. Neutral stimuli were consistently paired with Go trials, whereas smoking stimuli were paired with No-Go trials. 25% of trials in each gameplay session were No-Go trials, to ensure that players had to respond in the majority of trials and had to actively inhibit responses on No-Go trials (we included a reward system that is extensively explained in the online supplemental materials). Participants were instructed to complete at least five weekly 10-min sessions of game play. On average participants played the game 5.47 times (*SD* = 1.29; range = 2–9); they played 10.37 minutes (*SD* = 1.19; range = 8–13) per play session. These statistics are based on self-report data, but backend data of *HitnRun* roughly corroborated these self-reported estimates. Of the 54 participants in the game group, 48 (89%) complied with our instructions of playing *HitnRun* at least once a week.

Brochure

The freely available self-help brochure “Wat je zou moeten weten over stoppen met roken” (“What you should know about quitting smoking”) by the Trimbos Instituut (2014) was provided to participants in the control intervention group. This brochure aims to optimally prepare individuals for a quit attempt by addressing the benefits of quitting smoking, describing the withdrawal symptoms individuals will probably encounter and how to cope with these, and references to specialist support and supporting methods. Participants received a paper version of this 16-page brochure to read at least once in the intervention period and more often if they wanted to. On average participants read the brochure 3.65 times (*SD* = 2.46; range = 0–10). Of the 52 participants in the brochure group, only one (2%) reported to not have read the brochure at least one time.

Measures

Smoking-Specific Inhibitory Control

A modified version of the GNG task designed by Luijten et al. (2011) assessed inhibition of prepotent responses to smoking stimuli at preand posttest. Participants were presented with smoking-related (75 pictures) and neutral pictures (75 pictures), all different from the pictures included in *HitnRun*. Smoking-related pictures depicted smoking related objects such as a package of cigarettes, or people engaging in smoking behavior. Neutral pictures displayed neutral items, or people engaged in nonsmoking behavior. Participants were instructed to quickly and accurately respond to stimuli by pressing the spacebar (Go trials) or withhold from responding (No-Go trials) based on frame color. The frame color, purple versus turquoise, assigned to Go versus No-Go trials was counterbalanced across participants.

Participants completed one practice block and four test blocks of 150 trials each. Of the 600 trials, 75% were Go-trials and 25% were No-Go trials. Each pictorial stimulus was presented four times for 200 ms: three times as a Go stimulus, and once as a No-Go stimulus. The task was fast-paced, to increase task difficulty and therefore have more variability in the data. Trials were presented in a quasi-random order, separated by a black screen for a random duration varying between 1,020 ms and 1,220 ms. We restricted randomness of trial order such that no more than four Go trials and two No-Go trials followed each other. *M* reaction times on Go trials and mean accuracy on No-Go trials were calculated per for smoking and for neutral pictures separately.

Picture Evaluation

Participants were instructed to rate smoking pictures (60 pictures) and neutral pictures (60 pictures) on a continuous scale ranging from -100 (*negative*) to 100 (*positive*). In each trial, participants were specifically asked "How do you rate this picture?", and they could indicate their answer on a slider ranging from negative, to neutral, to positive. For participants in the game group, 80 of these pictures were trained during intervention as these pictures were part of the game (40 neutral and 40 smoking, labeled *trained pictures*). The remaining 40 pictures were novel pictures, only presented in the evaluation task (20 neutral and 20 smoking, labeled *untrained pictures*). In doing so, we were able to evaluate whether changes in smoking picture evaluation were limited to pictures repeatedly paired with Go or No-Go cues (the trained game pictures) or generalized to novel, untrained pictures (Veling et al., 2008). For participants in the brochure group all pictures (60 neutral and 60 smoking) were untrained, as these pictures were not included in the brochure. Pictures were rated at pretest and at posttest. *M* scores were calculated for untrained smoking and neutral pictures for all participants and additional mean scores for trained smoking and neutral pictures were calculated for the game group specifically.

Weekly Smoking Behavior

Weekly smoking behavior was assessed at preand posttest by multiplying two questions: a question measuring smoking quantity per day: "On a day that you smoke, how many cigarettes do you smoke on average? I smoke approximately . . . cigarettes a day" and a question measuring the number of smoking days: "How many days per week do you smoke on average?"

In-Game Performance

Every session that participants in the game group played *HitnRun*, in-game No-Go accuracy (hereafter in-game performance) was recorded for each No-Go trial. *M* accuracy scores were calculated for the second to the fifth gameplay session ($\geq$ 80 trials; in accordance with Veling et al., 2008) to preserve optimal accuracy while maintaining the vast majority of data. The first gameplay session was excluded, as participants played the first session in the lab and this session was played in "assessment mode." *Assessment mode* refers to a version of the game where no training was going on as both Go and No-Go cues were coupled with neutral and smoking pictures (similar to smoking-specific GNG task).

Expectations

Expectations for the effectiveness of each intervention were primed and assessed at pretest. This was done to rule out participants differing expectations as explanation for potential group differences on outcome measures (Boot et al., 2013; Crum et al., 2017). Participants were presented with brief descriptions of each intervention highlighting their potential for strengthening control to prime equal expectations; these descriptions are added to the online supplemental materials. Participants then indicated on a 6-point scale ranging from 1 (*not at all*) to 6 (*very much*) to what extent they thought that the brochure and the game would make them (a) "quit smoking," (b) "smoke less impulsively," (c) "have more control over their smoking behavior," and (d) "be more motivated to quit smoking." Sum scores were calculated for expectations related to the intervention participants were assigned to.

Strategy of Analysis

Prior to analyses, we checked for outliers ($\pm$ 3IQR; Walfish, 2006); and poor accuracy on No-Go trials at the GNG task ($<$ 30%). Consequently, five participants were excluded from analyses of GNG task performance, three participants were excluded from analyses regarding evaluation scores (i.e., incomplete data). In accordance with the intent-to-treat principle, all participants that were randomized to a group were included in the weekly smoking analyses (no-shows at posttest were included as nonabstinent, using the same values as at pretest). Therefore, only two participants were excluded from analyses regarding weekly smoking behavior (i.e., incomplete data). For in-game performance, all available pairwise information in the data was used. Fourteen participants were excluded from in-game data analyses, with either not enough play sessions including over 80 trials or with outliers in their data. Chi-square tests and *t*-tests were performed to examine whether randomization resulted in an equal baseline distribution of relevant participant characteristics (see Table 1). Significant differences at baseline were controlled for in subsequent analyses.

Behavioral accuracy on No-Go trials and reaction times on Go trials of the smoking-specific GNG task were tested with a Group (brochure vs. game: between-participants) × Picture Type (smoking vs. neutral: within-participants) × Time (pretest vs. Posttest: within-participants) RM-ANOVAs. Picture evaluations were analyzed with two separate RM-ANOVAs; a Picture Type × Training (trained vs. untrained) × Time Within-Subjects RM-ANOVA for participants in the game group compared effects between trained and untrained pictures. Furthermore, a Group × Picture Type × Time RM-ANOVA compared evaluations of untrained pictures between groups. We explored weekly smoking behavior with a Group × Time RM-ANOVA comparing group differences for smoking quantity per week. Finally, in-game performance was analyzed with a time (2nd vs. 3rd vs. 4th vs. 5th game session) RM-ANOVA in the game group to test whether performance increased over gameplay sessions. Greenhouse-Geisser corrections were used when the assumption of sphericity was violated. Follow-up *t*-tests with a Bonferroni correction for multiple comparisons were used when interaction effects were significant. Below, we only discuss significant effects; all statistics of RM-ANOVAs and follow-up *t*-tests are displayed in the online supplemental materials (see Tables S1, S2, and S3 in online supplementary materials). For readability purposes, we only report on the effects that are of direct interest for our research questions regarding picture evaluations; all other effects are discussed in the online supplemental materials (S5/S6).

In the online supplemental materials, we report on additional Bayesian RM-ANOVAs to inform the interpretation of null findings. In addition, results of latent growth curve analyses on in-game performance are reported in the online supplemental materials. These growth curve analyses were conducted to explore whether in-game performance increased across gaming sessions and whether these growth patterns were correlated with intervention effects.

Results

Table 1 presents descriptive statistics of participant characteristics and outcome variables per group at pretest. Participants in the brochure group had significantly higher expectations for their assigned intervention than participants in the game intervention group prior to the start of the intervention. To account for differences in expectations between intervention groups, we centered and included pretest expectations as a covariate in subsequent analyses. No further group differences were observed at pretest.

Smoking-Specific Inhibitory Control

No-Go Accuracy

The RM-ANOVA on No-Go accuracy only showed a main effect of Time, $F(1, 98) = 6.95$, $p = .010$, $\eta_p{}^2 = .07$, indicating that participants were less accurate on No-Go trials at posttest than at pretest (68% vs. 70%). Thus in contrast to our hypotheses, results suggest that the ability to inhibit responses in No-Go trials for both smoking and neutral pictures decreased over time in both intervention groups (see Figure S4 in online supplemental materials).

Go Reaction Times

Results from the RM-ANOVA on Go reaction times only showed a main effect of Time, $F(1, 98) = 19.58$, $p < .001$, $\eta_p^2 = .17$, showing that participants responded faster at posttest than at pretest ($M_{\text{pretest}} = 277$ ms vs. $M_{\text{posttest}} = 261$ ms). Thus, participants' responses on Go trials became faster over time but no intervention group differences were found (see Figure S5 in online supplemental materials).

General Inhibitory Control

Because of readability and length reasons, an intensive discussion of the general inhibitory control results can be found in the online supplemental materials. In summary, these results show that participants' general inhibitory control increased over time, but no group differences were found.

Picture Evaluation

Game Group: Effects on Trained Versus Untrained Pictures

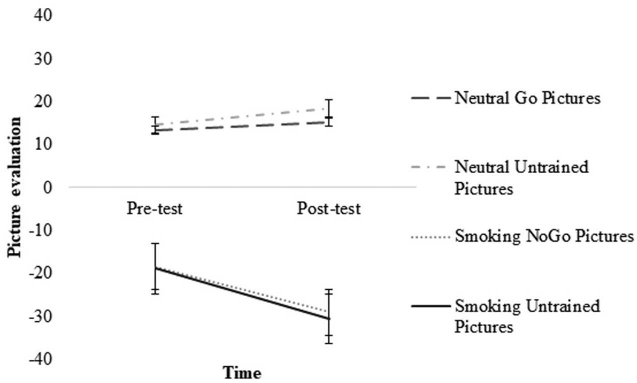
All effects of this analysis are discussed in the online supplemental materials (S5) and all accompanying follow-up tests are displayed in Table S2. A Picture Type × Training interaction was found, $F(1, 51) = 4.38$, $p = .041$, $\eta_p{}^2 = .08$. Follow-up tests showed that evaluations of untrained smoking-related pictures were less positive than untrained neutral pictures. Similarly, evaluations of trained smoking-related pictures were less positive than trained neutral pictures. Additional follow-up tests revealed that evaluations of smoking-related pictures and neutral pictures were similar for trained and untrained pictures. Note that although the interaction effect is significant, no significant differences are discovered with the follow-up tests that explain the significant interaction effect. A Picture Type × Time interaction was found, $F(1, 51) = 20.71$, $p < .001$, $\eta_p^2 = .29$; Follow-up tests showed that evaluations of smoking-related pictures were less positive at posttest than at pretest. In contrast, evaluations of neutral pictures remained constant over time. Additional follow-up tests revealed that smoking-related pictures were rated less positively than neutral pictures at pretest and at posttest. As predicted, evaluations of both trained and untrained smoking pictures in the game group decreased, whereas evaluations of neutral pictures remained the same (see Figure 1).

Between-Group Effects on Untrained Pictures

All effects of this analysis are discussed in the online supplemental materials (S6) and all accompanying follow-up tests are displayed in Table S3. We found a Group × Picture Type × Time interaction, $F(1, 100) = 4.31$, $p = .040$, $\eta_p{}^2 = .04$, with follow-up tests showing that untrained smoking-related pictures were evaluated less positively at posttest than pretest in the game group, but not in the brochure group. Although untrained neutral pictures were evaluated more positively at posttest than at pretest for the game group, they remained constant over time for the brochure group. Additional follow-up tests revealed no intervention group differences for untrained smoking-related pictures or untrained neutral pictures at pretest. Nor were there intervention group differences for untrained neutral pictures at posttest. In contrast, the game group evaluated untrained smoking-pictures less positively at posttest than the brochure group.

Figure 1

Untrained Versus Trained Picture Evaluations in Game Group



Note. Error bars represent standard errors.

Finally, follow-up tests showed that in both intervention groups smoking-related pictures were evaluated less positively than neutral pictures both at pretest and at posttest.

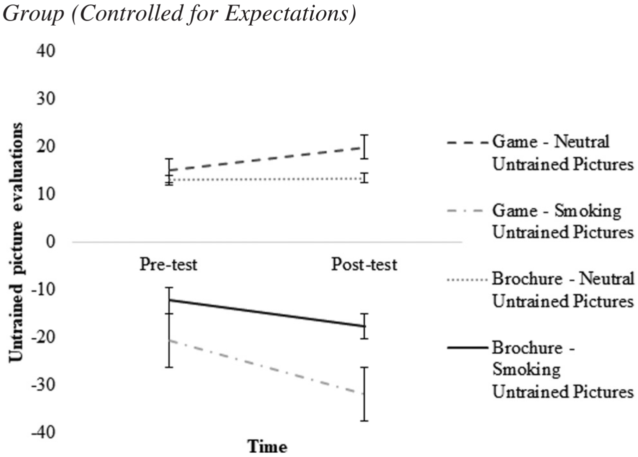
In summary, smoking-related pictures were evaluated less positively at posttest than at pretest in the game group, but not in the brochure group. Neutral picture evaluations remained the same over time in the brochure group, whereas they showed a small increase in the game group (see Figure 2).

Behavioral Outcomes

A Group × Time RM-ANOVA on number of cigarettes smoked per week only revealed a main effect of Time, $F(1, 101) = 113.87$, $p < .001$, $\eta_p^2 = .53$, indicating a general decrease in cigarettes a week from pretest to posttest (see Figure S6 in online supplemental materials). Thus, both intervention groups showed a decrease in number of cigarettes over time, but there were no differences between groups.[2]

Figure 2

Untrained Picture Evaluations in Game Group and Brochure Group (Controlled for Expectations)



Note. Error bars represent standard errors.

In-Game Performance

A RM-ANOVA on mean in-game No-Go accuracy revealed a main effect of time, $F(3, 117) = 5.19$, $p = .002$, $\eta_p^2 = .12$, indicating a general increase in gaming performance from the second play session to the fifth play session (see Figure S7 in online supplemental materials). In addition, we conducted latent growth curve analyses on in-game performance to explore whether in-game performance increased across gaming sessions and whether these growth patterns were correlated with intervention effects. These analyses and results are extensively reported in the online supplemental materials. The most important take-away from these analyses is that participants were able to increase in-game performance across training sessions, and that these increases in in-game performance were associated with stronger decreases in weekly smoking at posttest.

Discussion

The current two-armed experimental study tested the effects of the game intervention *HitnRun* in young smoking adults who were motivated to quit smoking. The game intervention was compared to an active brochure intervention to test basic mechanisms of change argued to be responsible for the behavioral effects of GNG trainings, as well as effects on weekly smoking. Contrary to our expectations, GNG task performance revealed a decrease in smoking No-Go accuracy and an improvement in reaction times on Go trials for both intervention groups, suggesting a speed–accuracy trade-off after intervention. Thus, no training effects on smoking-specific inhibitory control were found, and we also did not find a transfer effect from the GNG training to general inhibitory control. A robust decrease in perceived attractiveness of smoking pictures was observed in the game group, but not in the brochure group. This finding is in line with the BSI account. Finally, no differences were found between intervention groups on weekly smoking.

Top-Down Control Theory

We did not find the expected superior effects of the game group compared to the brochure group on smoking-specific inhibitory control. The decrease in No-Go accuracy and the increase in Go reaction times may be explained by a strong speed–accuracy trade-off (Zhao et al., 2016). This means that an increased speed came at the cost of decreased overall accuracy, which is a phenomenon especially observed in smokers when exposed to short presentation times and low no-go probability (Zhao et al., 2016).

In addition, the decrease in No-Go accuracy in both intervention groups may be due to repeated testing effects or participants reduced attention. For a proper assessment of inhibitory control capacity we need many trials, which makes the task repetitive and boring (Forman et al., 2018), especially at posttest. Even more so when participants have been trained with a game version of this task to make the training more fun (Boendermaker et al., 2016). Thus, it could have been the case that participants at posttest did

[2] Abstinence analyses showed the same overall results, χ^2 (1, n = 106) = 0.21, p = .648: over the whole sample, 39 participants (37%; participants who did not show up for posttest were rated as non-abstinent) were abstinent at posttest. Of these 39 participants, 21 (54%) were randomized to the game group and 18 (46%) to the brochure group.

pay less attention to the task after repeated exposure to *HitnRun* and just pressed the button after stimulus presentation, which might explain the increases in reaction times and decreases in accuracy over time. This explanation does not only play a role in the current study but may also help us understand a broad array of the mixed findings in the area of cognitive training research.

Another explanation may be found in wrongfully assuming that GNG training reinforces a top-down executive control process that directly increases the capacity to resist impulses toward the behavior one wants to reduce (e.g., Andrés, 2003). Yet, this theoretical assumption has only been tested once before, by using a comparative prepost assessment of inhibitory capacity to study effectiveness of GNG training on top-down inhibitory control (i.e., Adams et al., 2017). Our study, in accordance with Adams and colleagues, did not find evidence for the common assumption that top-down inhibitory control is strengthened by GNG training. Probably the most plausible explanation for our findings is thus that the behavioral effects found in many studies (Allom et al., 2016; Jones et al., 2016; Turton et al., 2016) may not result from top-down inhibitory control improvements, but rather result from changes in the subjective evaluation of to-be-inhibited stimuli or by direct bottom-up stimulus-stop associations that have been acquired (Veling et al., 2008, 2017).

Behavior Stimulus Interaction Theory

As predicted, a robust decrease in perceived attractiveness of smoking pictures was observed in the game group, yet not in the brochure group. This decrease in perceived attractiveness of smoking stimuli occurred for both trained pictures, which were consistently mapped onto No-Go cues in *HitnRun*, and novel, untrained pictures. Neutral untrained picture evaluations in the brochure group as well as neutral trained picture evaluations in the game group remained constant over time, whereas neutral untrained picture evaluations in the game group showed a small increase.

By design, we were not able to compare the brochure group and game group with each other on all aspects of picture evaluation, since participants in the brochure group were not exposed to training. Therefore, we analyzed within game group differences between trained and untrained pictures only. According to BSI theory, a devaluation effect exists when GNG training results in a larger decrease in attractiveness of No-Go stimuli compared to Go or untrained No-Go stimuli (Chen et al., 2016, 2017). This strict definition of the devaluation effect is set because it allows us to reject the explanation of regression to the mean, a likely explanation without a comparison group. In our study we could only identify a devaluation effect by comparing the evaluations of trained versus untrained smoking pictures, as we exclusively included neutral pictures as Go stimuli. We did not include smoking pictures as Go stimuli based on the ethical consideration that we did not want to train participants toward smoking related stimuli (e.g., Chen et al., 2016). Based on this, our results revealed no devaluation effect. That is, within the game group, we found similar decreases in trained and untrained smoking picture evaluations.

Yet, the current study was set up to study whether GNG training, which so far was mostly investigated in a fundamental research setting, could be used as a mechanism of change eventually targeting smoking cessation in youth. Well-controlled laboratory experiments and accompanying results do not mean much if they do not hold in the real world. This translation from fundamental research to clinical settings is necessary, but also not without challenge. In our study specifically, central to considering the impact of a GNG training is the issue of generalization from trained to untrained stimuli. In the current study we indeed found significant decreases in evaluations of untrained smoking stimuli which did not differ from the decrease in trained smoking stimuli, which can be explained by two possible reasons. First, the results that we found could be explained as merely a case of regression to the mean (Cohen et al., 2013).

Second, an alternative explanation could be that our results are an indication that transfer of decreased evaluations from the trained pictures to the untrained pictures may have occurred (Chen et al., 2016). This explanation resonates with a study by Chen et al. (2018) among healthy college students who showed that food No-Go pictures were evaluated less positively than food Go pictures, yet they did not find significant differences between the untrained food pictures and food No-Go pictures. These findings are interpreted as evidence for the clinical potential of GNG training. Additionally, in our current study we found a significant decrease in evaluations for untrained smoking-related pictures in the game group and not in the brochure group. This could indicate actual transfer of training in the game group which did not occur in the brochure group thereby eliminating regression to the mean. However, based on the current study design, it is not possible to pinpoint whether our results might be explained by regression to the mean or transfer of training effects to untrained stimuli, since for ethical reasons, and in contrast to Chen et al. (2018), we did not include smoking pictures as Go stimuli to check for potential differences between evaluations of Go and No-Go stimuli. Therefore, we can neither rule out the possibility of the lack of a GNG training effect due to regression to the mean as the transfer of the GNG training effect to untrained pictures. Yet, the between group comparison with the brochure group gives us some tentative evidence for transfer of decreased evaluations from trained to untrained pictures, as only a decrease in evaluations for smoking-related pictures was observed in the game group (and not in the brochure group). In conclusion, more research in a translational context is needed to better understand whether GNG training could play a role in smoking cessation interventions for youth.

Overall, it is important to note that many of our hypothesized effects were not significant. Our speculation would be that part of the nonsignificant results might be explained by the fact that we measured top-down control as the underlying mechanism of change, whereas effects were more so driven by decreased evaluations of substance-related stimuli. However, part of the nonsignificant effects might also be explained by a mismatch between the laboratory tasks used to measure GNG training effects and the real world training game. This idea is supported by our findings showing that although we did not find effects of the game GNG training on top-down control in a laboratory task, we showed increases in game performance over game sessions in the game environment itself. This is again a challenge that is related to transfer of GNG training to a real world context. The fact that we observed different effects in laboratory tasks versus in-game training data shows the importance of combing multiple measurement techniques in the context of translational research.

Limitations and Recommendations

Despite the rigorous two-armed experimental design used in the current study and the relatively large sample size, some limitations should be noted. The chosen control condition might have attributed to similar results in both intervention groups; exposure to self-help smoking cessation information might have resulted in beneficial effects for the active control intervention group as well (Sussman & Sun, 2009). Also nonspecific factors, such as mindset or learning effects could have boosted or decreased effects in both intervention groups (Crum et al., 2017; Dweck, 2006; McCuller et al., 2006). In a recent study by Jones et al. (2018), in which different versions of inhibitory control trainings were tested to reduce alcohol use in adults, similar results as in the current study were encountered: participants showed similar decreases in alcohol use in all groups, including the active control group. The authors report that nonspecific effects of the intervention might have effectively served as alternative form of intervention which could have obscured the inhibitory control training effects. Although these nonspecific effects can be very valuable and should not be taken away from interventions (Crum et al., 2017), future research could include a passive control group (i.e., a waitlist group) and measurements of nonspecific factors to control for and disentangle these alternative explanations. In addition, to be able to make the comparison between GNG trainings with or without a game format, future studies would benefit from the inclusion of an extra control group that would receive a traditional GNG training as intervention. The inclusion of this extra control group could also clarify the possibility of transfer effects from trained to untrained smoking pictures. Another limitation is our sole reliance on self-report smoking data.

Although we aimed to enhance training effects by preserving effective components of traditional GNG trainings while using several motivating elements of the game format, several factors may have interacted with *HitnRun* and could have potentially reduced the effects in our study. For example, whereas traditional training keeps the duration of each trial constant (Lawrence et al., 2015; Veling et al., 2014); *HitnRun* included a gradual increase in running speed. Trials became shorter over time which increased the difficulty of training, this could have resulted in players being unable to keep up leading them to get frustrated or giving up. Future design iterations should invest in more play testing time to improve the sensitivity of the dynamic adjustment to optimally match participants' individual differences in performance.

Another design element of *HitnRun* that may have impacted the effectiveness of training is the reward system. This system was built in such a way that participants were only rewarded for consecutive correct Go trials, but not for correct No-Go trials as we did not want to strengthen smoking-reward associations. This may have resulted in a play strategy whereby played tried to obtain a high score by showing continuous Go responses and forgo inhibition altogether. This again shows that balancing effective components of traditional GNG trainings and motivating elements of game design is incredibly difficult. Yet, to overcome common challenges of interventions (e.g., attrition, stigma, limited scalability), we argue that simply encasing conventional training in a game-shell is unlikely to produce motivational benefits (Scholten & Granic, 2019). It remains a challenge to adjust our psychological lab tasks enough so that they feel like an authentic gaming experience, but the motivational and engagement benefits seem worth pursuing (Forman et al., 2018).

Qualitative interviews after the intervention period gave us some insight in the player experience. We found out that participants did not like the duration of play time (i.e., 10 minutes once per week); they reported that it was 10 min of playing was too long and that they got bored after a few minutes. Furthermore, participants indicated that they would like to carry the game with them at all times, such that they play the game at moments they would normally want to smoke. Shortening the play sessions while increasing the number of sessions per week and bringing the game to mobile to assist youth and young adults at critical moments during their quit attempts could be valuable adaptations to make the game more attractive and effective.

Conclusion

In conclusion, the current study revealed similar decreases for both intervention groups in smoking-specific inhibitory control accuracy, faster reaction times from pre- to posttest, and similar decreases in weekly smoking behavior. Yet, the game group showed a decrease for evaluations of untrained smoking stimuli, whereas the brochure group did not. These results are potentially in line with earlier work suggesting that GNG training does not necessarily train top-down control, but functions instead via decreased evaluations of substance-related stimuli. Furthermore, *HitnRun* was capable of increasing in-game performance across training sessions, and, based on exploratory analyses in the online supplemental materials, these increases in in-game performance were associated with stronger decreases in weekly smoking at posttest, thereby showing some potential for new game iterations. However, more research is warranted since the design and results of this study do not allow us to rule out the possibility of regression to the mean versus transfer from trained to untrained smoking stimuli. Because the motivational benefits of game-based interventions remain promising, it is important that future studies investigate factors that could promote effective GNG training within game formats. Furthermore, besides investigating the potential of GNG training, it is important to further explore other evidence-based mechanisms (e.g., peer processes, self-efficacy, motivational interviewing) to smoking interventions. Smoking cessation is especially difficult in at-risk youth and young adults, and therefore requires a multicomponent intervention that is dynamically adjustable to individual needs to reach as many young people as possible.

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