Research review

Inhibitory control training for appetitive behaviour change: A meta-analytic investigation of mechanisms of action and moderators of effectiveness

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Abstract

Inhibitory control training (ICT) is a novel intervention in which participants learn to associate appetitive cues with inhibition of behaviour. We present a meta-analytic investigation of laboratory studies of ICT for appetitive behaviour change in which we investigate candidate mechanisms of action, individual differences that may moderate its effectiveness, and compare it to other psychological interventions. We conducted random-effects generic inverse variance meta-analysis on data from 14 articles (18 effect sizes in total). Participants who received ICT chose or consumed significantly less food or alcohol compared to control groups (SMD = 0.36, 95% CI [0.24, 0.47]; Z = 6.18, p < .001; P² = 71%). Effect sizes were larger for motor (Go/No-Go and Stop Signal) compared to oculomotor (Antisaccade) ICT. The effects of ICT on behaviour were comparable to those produced by other psychological interventions, and effects of ICT on food intake were greater in participants who were attempting to restrict their food intake. The magnitude of the effect of ICT on behaviour was predicted by the proportion of successful inhibitions but was unrelated to the absolute number of trials in which appetitive cues were paired with the requirement to inhibit, or the contingency between appetitive cues and the requirement to inhibit. The effect of ICT on cue devaluation (primarily assessed with implicit association tests) was not statistically significant. Our analysis confirms the efficacy of ICT for short-term behaviour change in the laboratory, and we have demonstrated that its effectiveness may depend on pairings between appetitive cues and successful inhibition. We highlight the need for further research to translate these findings outside of the laboratory.

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1. Introduction

Inhibitory control, also referred to as response inhibition, can be conceptualised as the ability to stop, change or delay a behavioural response (Logan, Cowan, & Davis, 1984), and it is an important component of both executive functioning and impulsivity (Bickel, Jarmolowicz, Mueller, Catchalian, & McClure, 2012; Miyake et al., 2000). There is substantial overlap between 'inhibition' and self-regulation, with an estimated 80–90% of self-regulation requiring some form of inhibitory control (Baumeister, 2014). Self-regulatory behaviours are diverse and encompass inhibition of internal states such as emotions and urges, and inhibition in response to external triggers such as stopping at red traffic signals. Poor self-regulation and inhibitory control are associated with the development of impulse-control disorders as well as maladaptive behavioural traits such as aggression (Groman, James, & Jentsch, 2009; Kooijmans, Scheres, & Oosterlaan, 2001). If humans did not have the ability to regulate and inhibit their behaviour, they would immediately respond to the most motivationally-relevant stimulus in the environment and be unable to adjust their behaviour when required to do so. Therefore, the importance of inhibitory control for motivated behaviour cannot be understated, and without it we would be 'doomed' (Verbruggen, Best, Bowlditch, Stevens, & McLaren, 2014).

1.1. Computerised measures of inhibitory control

Inhibitory control can be measured with a variety of computerised tasks, including the Stop Signal (Logan et al., 1984), Go/No-Go (Newman & Kosson, 1986), and Antisaccade tasks (Hallett, 1978). The Stop Signal and Go/No-Go tasks assess the ability to inhibit a pre-potent or habitual motor response when prompted by a cue, for example a stop signal or no-go stimulus. The tasks place emphasis on successful inhibition (i.e. stopping a response) in a context in which rapid responding is required on the majority of trials (Verbruggen & Logan, 2008; Verbruggen, McLaren, & Chambers, 2014). Inhibitory control on these tasks is thought to represent an internal race between two competing processes: a 'go' process and a 'stop' process. Should the go process win the race then the pre-potent behaviour will be executed, but should the stop process win then the pre-potent behaviour will be successfully inhibited (Band, van der Molen, & Logan, 2003). These computerised measures are widely used in the literature and each yields a valid index of inhibitory control (Diamond, 2013), although each task may capture a slightly different aspect of it. For example, in the Go/No-Go task the requirement to inhibit is consistently mapped on to a no-go cue (or cues). By contrast, in the Stop Signal task, a 'go' cue is always presented before the stop signal, and the triggering cue and the stop signal are not consistently paired (Verbruggen & Logan, 2008). The Antisaccade task requires participants to avoid making a saccade (eye movement) towards a specific stimulus that appears following a cue, and thus measures oculomotor rather than motor inhibition. These tasks have led to the recognition that there are at least two types of inhibitory control: action restraint in which the decision to inhibit is made from the onset (Go/No-Go tasks) and action cancellation in which the decision to inhibit occurs after implementation of the pre-potent response (Stop Signal and Antisaccade tasks; Eagle, Bari, & Robbins, 2008; Verbruggen & Logan, 2008).

1.2. Associatively mediated inhibitory control

It is commonly assumed that inhibitory control is engaged intentionally. However, recent observations suggest inhibitory control can be engaged automatically in the absence of intentions to do so. In a series of experiments, Verbruggen et al. (2009) integrated the primes ‘Stop’, ‘Go’ or ‘****’ into a Stop Signal task. Although the primes were unrelated to the required behavioural response (to respond or inhibit), the prime ‘Stop’ exerted a slowing effect on go reaction times, whereas the prime ‘Go’ exerted a slowing effect on inhibitory control. Other studies have demonstrated that inhibitory control can be influenced by the presentation of subliminally presented cues (Parkinson & Haggard, 2014), and that inhibitory control becomes more efficient if the requirement to inhibit is consistently mapped to specific cues (Verbruggen & Logan, 2008). It seems that inhibitory control can be engaged automatically by environmental cues that have been reliably paired with the requirement to inhibit. To give a real-world example, consider the response of an experienced driver who is approaching an intersection and the traffic signal turns red: The driver will engage the brakes, and this may be an automatic response to the
environmental cue rather than a deliberate act (McLaren & Verbruggen, in press).

Theoretical models of action control suggest close correspondence between an action axis that spans from behavioural activation to inhibition, and a valence axis that spans from reward to punishment. In other words, appetitive, reward-related cues should be associated with activation of motor behaviour, whereas aversive, punishment-related cues should be associated with inhibition of behaviour (McLaren & Verbruggen, in press; Verbruggen, Best, et al., 2014; Verbruggen, McLaren, et al., 2014). Experimental research lends support to these claims. On the one hand, positively valenced or rewarding stimuli are more likely to trigger instrumental responding or behavioural approach, irrespective of the instrumental consequences of those actions. On the other hand, negatively valenced stimuli or stimuli associated with punishment are more likely to trigger inhibition of behaviour (Guitart-Masip et al., 2012). Importantly, the aforementioned theoretical models claim that the relationship between activation/inhibition and stimulus valence may be bidirectional, and these claims have received some support: Repeated approach responses directed toward neutral cues increases positive evaluations of those cues (Cacioppo, Priester, & Berntson, 1993; Woud, Becker, & Rinck, 2008; Woud, Maas, Becker, & Rinck, 2013) whereas repeated inhibition of behaviour in response to specific cues leads to devaluation of those cues (Wessol, O'Doherty, Berkebile, Lindermann, & Aron, 2014) such that they are evaluated more negatively.

### 1.3. Inhibitory control in appetitive behaviours and associated disorders

Obesity and substance abuse have complex aetiology, but dysfunction in some psychological processes may be common to both. In particular, contemporary theories highlight key roles for the hyper-valuation of reward-associated stimuli combined with the inability to successfully engage inhibitory control, in the development and maintenance of both conditions (Volkow, Wang, Fowler, & Telang, 2008; Volkow, Wang, Tomasi, & Baler, 2013). A recent meta-analysis confirmed small but robust associations between inhibitory control deficits and substance use (including alcohol use) disorders (Smith, Mattick, Jamadar, & Iredale, 2014). Similarly, inhibitory control deficits have been reported in obese individuals (Nederkoorn, Smulders, Havermans, Roefs, & Jansen, 2006). Importantly, these deficits in inhibitory control may exist pre-morbidly to substance use and obesity, suggesting a causal role for (poor) inhibitory control in unhealthy behaviours and associated psychiatric and medical conditions (Ersche et al., 2012; Fernie et al., 2013; Nederkoorn, Houven, Hofmann, Roefs, & Jansen, 2010).

As discussed in the previous section, there are close links between stimulus evaluation, behavioural approach and avoidance tendencies evoked by stimuli, and the capacity of those stimuli to facilitate or interfere with inhibitory control. These links may explain why appetitive or rewarding cues such as pictures of chocolate or beer (Field, Kriennan, Eastwood, & Child, 2008; Kemps, Tiggemann, Martin, & Elliott, 2013) evoke behavioural approach responses, in addition to transient impairments in inhibitory control (Adams, Ataya, Attwood, & Munafò, 2013; Jones & Field, 2015; Meule et al., 2014; Weaver & Fillmore, 2012). On the basis of these findings, some theorists proposed that temporary impairments in inhibitory control provoked by cues that have been paired with appetitive reward might influence subsequent consumption of those rewards, and by extension these cue-provoked impairments in inhibitory control may play a role in the development of obesity and substance abuse (De Wit, 2009; Jones, Christiansen, Nederkoorn, Houven, & Field, 2013).

### 1.4. Inhibitory control training

The observation that inhibitory control can be associatively mediated suggests promising new avenues for behavioural interventions for appetitive disorders (see Jones et al., 2013; Verbruggen, Best, et al., 2014; Verbruggen, McLaren, et al., 2014; Wiers, Gladwin, Hofmann, Salenick, & Riddershof, 2013). During ‘inhibitory control training’ (ICT), participants complete an inhibitory control task in which the requirement to exercise inhibitory control is paired with cues related to food or alcohol, before the effects of this training on choice and/or consumption of food or alcohol are measured. For example, Jones and Field (2013) demonstrated that participants who completed a Stop Signal task in which alcohol images were paired with inhibition subsequently consumed less alcohol than a group of participants in whom inhibition was paired with neutral cues. Similarly, participants who learnt to associate food images with inhibition on a Go/No-Go task subsequently consumed less of those foods when given access to them (Houben & Jansen, 2011).

A recently published meta-analysis demonstrated small but significant effects of ICT on both food ($d = 0.37$) and alcohol consumption ($d = 0.43$) in the laboratory (Alom, Mullan, & Hagger, 2015). This analysis demonstrated larger effects for Go/No-Go rather than Stop Signal training tasks, with no difference in effect sizes between objective (ad-libitum intake, choice) and subjective (self-report) outcomes. Alom and colleagues also examined the relationship between the total number of trials during ICT and subsequent behavioural effects of ICT, and found that this relationship was not statistically significant. However, this analysis is not an appropriate test of the theoretical claim that the number of cue-inhibition pairings should determine the effects of ICT on behaviour, because these trials do not constitute the majority of trials during ICT; indeed, in some studies the proportion of such trials is very low (e.g. 16.6% in Van Koningsbruggen, Veling, Stroebe, & Aarts, 2014).

Our primary aim was to replicate and extend the meta-analysis reported by Alom et al. (2015) in order to investigate the influence of ICT on appetitive behaviour in the laboratory. Our analysis differs from that reported by Alom et al. (2015) in several important ways. First, we included additional (currently unpublished) datasets from several different laboratories. Second, we incorporated studies that used oculomotor inhibition tasks in order to investigate if inhibition of oculomotor versus motor responses would have comparable effects on appetitive behaviour. Third, we conducted additional analyses to test theoretical predictions about the psychological mechanisms that underlie the effects of ICT. Specifically, we tested the claim that ICT effects arise because participants form associations between appetitive cues and inhibition of behaviour (Verbruggen, Best, et al., 2014; Verbruggen, McLaren, et al., 2014) by quantifying associations between the effects of ICT on behaviour and (1) the number of cue-specific inhibition trials (or ‘critical’ trials), (2) the contingency between appetitive cues and the requirement to inhibit and (3) the degree to which participants were able to successfully inhibit responding on critical trials. We also investigated if ICT resulted in devaluation of the appetitive cues that were paired with inhibition, which is a test of a related (but distinct) theoretical prediction about its mechanism of action (Veling, Holland, & van Knippenberg, 2008; Wessel et al., 2014). Fourth, we contrasted effects of ICT with effects produced by other psychological interventions (brief interventions, implementation intentions, and cognitive bias modification). Finally, we investigated whether individual differences in attempts to restrict food intake would moderate effects of ICT, as has been reported in some studies (Houben & Jansen, 2011; Lawrence, Verbruggen, Morrison, Adams, & Chambers, 2015; Veling, Aarts, & Papes, 2011).
2. Methods

2.1. Information sources and search strategy

Literature searches were guided by Preferred Reporting Items for Systematic Review (PRISMA). We searched three electronic databases: Scopus (134 articles), PubMed (901 articles) and Psy- cInfo (820 articles), between August and September 2014. Searches included a combination of key words relevant to inhibitory control tasks, inhibition training or modification, food or alcohol, and consumption or choice. See Supplementary materials for full search terms. Searches were limited from 2004 onwards because we are unaware of any research on ICT prior to 2004, and preliminary searches confirmed this. Supplementary searches of these databases (March 2015) prior to submission identified one further article (Houben & Jansen, 2015). Manual searches were conducted on the reference lists of identified articles and lead authors of all articles were contacted for any unpublished data or manuscripts, in order to reduce the risk of publication bias. In response to this request for unpublished data, four effect sizes from two PhD theses were included (Adams, 2014; Di Lemma, in preparation).

2.2. Eligibility criteria

All studies had to meet the following criteria in order to be included in the meta-analysis:

2.2.1. Participants

We included studies that tested human participants over the age of 18 years. Interventions: We included studies with an experimental design that implemented ICT that was intended to pair appetitive cues with inhibition of responding, and compared this with an appropriate control intervention.

2.2.2. Outcome measure

Studies were required to have an outcome measure of appetitive behaviour related to alcohol or food-consumption, such as ad- libitum intake or choice of alcohol or food, and this measure had to be administered immediately after ICT.

2.3. Data extraction and coding (Fig. 1)

Two independent coders performed the searches and identified the relevant studies. A total of 1459 unique articles were screened via title and abstract, of these 1410 were excluded without disagreement. Data were extracted by one person and cross-checked by two others. In cases where a study met the inclusion criteria but insufficient information was provided to compute the effect size, data were requested from the corresponding author. All authors responded and provided data within one month. We also retrieved data from an online repository for one article (Lawrence et al., 2015).

2.4. Variables of interest (Table 1)

We extracted and coded a number of variables including the absolute number of critical trials (trials in which appetitive cues were paired with the requirement to inhibit), the contingency between appetitive cues and the requirement to inhibit on critical trials, the mean percentage of successful inhibitions on critical trials, the type of ICT task, study design (within-subjects or between-subjects), information about the control condition(s), population studied including inclusion and exclusion criteria, age and gender distribution of the sample, and sample size.

2.5. Statistical analyses

We calculated the standardised mean difference (SMD) and the standard error of this difference (SMD-SE) between ICT and control conditions (Durlak, 2009). This statistic was calculated as $SMD = (M_i - M_c) / S_p$, where $M_i$ is the mean of the intervention group, $M_c$ is the mean of the control group, and $S_p$ is the pooled within-group standard deviation. These parameters were used for the generic inverse variance meta-analytic method, which
Table 1
Summary of studies included in the meta-analyses.

| Authors and study | Participants and design | ICT manipulation (contingency between inhibition and image type) | Outcome (DV used in analyses) |
|-------------------|-------------------------|---------------------------------------------------------------|--------------------------------|
| Adams et al. (unpublished a) | N: 132 (67 ICT) | Mean age: 22.65 years<br>93.15% Female<br>Inclusion criteria: Chocolate cravers (>10 score on ACQC) and restrained eaters.<br>Exclusion criteria: Current dieters or history of eating disorders<br>Mean BMI: 24.6<br>Between-subjects design | Stop Signal task<br>ICT: inhibit to chocolate images (87.50% contingency), respond to non-food images<br>Control: double response to chocolate (87.50% contingency) images, single response to non-food images<br>480 trials: 80 critical<br>Average successful inhibition — 69.76% | Ad-libitum: Consumption of crisps and chocolate (Kcals) |
| Adams et al. (unpublished b1) | N: 66 (34 ICT) | Mean age: 21.26 years<br>92.58% Females<br>Inclusion criteria: Restrained eaters<br>Exclusion criteria: Current dieters or history of eating disorders<br>Mean BMI: 24.6<br>Between-subjects design | Stop Signal task<br>Healthy, unhealthy and non-food images<br>ICT: inhibit to unhealthy food (88.90% contingency) images, single response to non-food images<br>228 trials: 72 critical<br>Average successful inhibition — 67.51% | Ad-libitum: Consumption of healthy and unhealthy foods (Kcals) |
| Adams et al. (unpublished b2) | N: 82 (40 ICT) | Mean age: 22.13 years<br>90.77% Female<br>Inclusion criteria: Chocolate cravers<br>Exclusion criteria: Aged 18–30, failure to attend both sessions, contraindications to alcohol.<br>Mean AUDIT score: 11.25<br>Between-subjects design | Go/No-Go task<br>Healthy, unhealthy and non-food images<br>ICT: inhibit to unhealthy foods (100% contingency) and respond to healthy food images<br>228 trials: 72 critical<br>Average successful inhibition — 95.67% | Ad-libitum: Consumption of healthy and unhealthy foods (Kcals) |
| Bowley et al. (2013) | N: 39 (19 ICT) | Mean age: 20.95 years<br>23.07% Female<br>Inclusion criteria: Aged 18–30, exclusion criteria: AUDIT >20, failure to attend both sessions, contraindications to alcohol.<br>Mean AUDIT score: 11.25<br>Between-subjects design | Go/No-Go task<br>Beer and water images<br>ICT: inhibit to beer (100% contingency) images and respond to water images<br>80 trials: 40 critical<br>Average successful inhibition data not available. | Ad-libitum: Beer as a percentage of total fluid consumed during ‘taste test’ |
| Di Lemma et al. (unpublished) | N: 60 (30 ICT) | Mean age: 20.32 years<br>70.0% Female<br>Inclusion criteria: Heavy drinkers, >14 UK units per week for females or >21 units for males<br>Exclusion criteria: No history of alcohol-related problems.<br>Between-subjects design | Go/No-Go task<br>Alcohol and neutral images<br>ICT: inhibit to alcohol (90% contingency) images and respond to neutral images<br>Control: respond to alcohol images and inhibit to neutral (90% contingency) images<br>480 trials: 216 critical<br>Average successful inhibition — 99.33% | Ad-libitum: Alcoholic drinks as a percentage of total fluid consumed during ‘taste test’ |
| Houben et al. (2011) | N: 52 (25 ICT) | Mean age: 22.37 years<br>63.46% Female<br>Inclusion criteria: More than 12 (male) or 10 (female) alcohol beverages per week<br>Exclusion criteria: None stated<br>Between-subjects design | Go/No-Go task<br>Beer and water images<br>ICT: inhibit to beer (100% contingency) images and respond to water images<br>80 trials: 40 critical<br>Average successful inhibition — 99.20% | Ad-libitum: Amount of beer consumed during ‘taste test’ (ml) |
| Houben and Jansen (2011) | N: 43 (22 ICT) | Mean age: 20.08 years<br>100% Female<br>Inclusion criteria: Chocolate cravers (>10 score on ACQC)<br>Exclusion criteria: None stated<br>Mean BMI: 23.4<br>Between-subjects design | Go/No-Go task<br>Chocolate, snack food and empty plate images<br>ICT: inhibit to chocolate (100% contingency) images and respond to empty plate images<br>Control: respond to chocolate images and inhibit to empty plate (100% contingency) images<br>320 trials: 160 critical<br>Average successful inhibition — 98.99% | Ad-libitum: Chocolate consumption (grams) |
| Houben and Jansen (2015) | N: 41 (21 ICT) | Mean age: 21.13 years<br>100% Female<br>Inclusion criteria: Female participants<br>Exclusion criteria: Underweight (BMI <18.5), dislike of chocolate during taste test<br>Mean BMI: 22.18<br>Between-subjects design | Go/No-Go task<br>Chocolate, snack food and empty plate images<br>ICT: inhibit to chocolate (100% contingency) images and respond to empty plate images<br>Control: respond to chocolate images and inhibit to empty plate images (100% contingency)<br>320 trials: 160 critical<br>Average successful inhibition — 98.51% | Ad-libitum: Chocolate consumption (kcal) |
| Authors and study | Participants and design | ICT manipulation (contingency between inhibition and image type) | Outcome (DV used in analyses) |
|-------------------|-------------------------|---------------------------------------------------------------|------------------------------|
| **Jones and Field (2013) Study 1** | N: 60 (30 ICT) | Mean age: 20.79 years<br>54.44% Females | Stop Signal task<br>Beer and neutral images<br>ICT: inhibit to beer (90% contingency) images and respond to neutral images<br>Control: respond to beer images and inhibit to neutral (90% contingency) images<br>*Control: respond to both beer and neutral cues, never inhibit<br>240 trials: 108 critical<br>Ad-libitum: Beer as a percentage of total fluid consumed during 'taste test'<br>Mean AUDIT score: 14.65<br>Between-subjects design | **Ad-libitum: Beer as a percentage of total fluid consumed during 'taste test'**<br>**Mean AUDIT score: 13.85**<br>**Between-subjects design** |
| **Jones and Field (2013) Study 2** | Mean age: 21.18 years<br>53.33% Female | Inclusion criteria: Heavy drinkers, >14 UK units per week for females or >21 units for males, liking of beer<br>Exclusion criteria: History of alcohol-related problems, normal or corrected vision. | Antisaccade task<br>Beer and neutral images<br>ICT: inhibit to beer (80% contingency) images and respond to neutral images<br>Control: respond to beer images and inhibit to neutral (80% contingency) images<br>240 trials: 96 critical<br>Average successful inhibition = 87.43%<br>Mean BMI: 22.9<br>Between-subjects design | **Ad-libitum: Beer as a percentage of total fluid consumed during 'taste test'**<br>**Mean BMI: 22.9**<br>**Between-subjects design** |
| **Lawrence et al. (2015) Study 1** | N: 54 (29 ICT) | Mean age: 24.00 years<br>60.0% Females | Stop signal task<br>Food and non-food images<br>ICT: inhibit to food (87.5% contingency) images, single response to non-food images<br>Control: double response to food (87.5% contingency) images, single response to non-food images<br>480 trials: 140 critical<br>Average successful inhibition = 83.12%<br>Mean BMI: 22.9<br>Between-subjects design | **Ad-libitum: Consumption of crisp (Kcal)**<br>**Mean BMI: 22.9**<br>**Between-subjects design** |
| **Lawrence et al. (2015) Study 2** | N: 90 (46 ICT) | Mean age: 24.12 years<br>72.94% Females | Stop Signal task<br>Food and non-food images<br>ICT: inhibit to food (87.5% contingency) images, single response to non-food images<br>Control: double response to food (87.5% contingency) images, single response to non-food images<br>480 trials: 140 critical<br>Average successful inhibition = 83.12%<br>Mean BMI: 23.5<br>Between-subjects design | **Ad-libitum: Consumption of crisp and chocolate (Kcal)**<br>**Mean BMI: 23.5**<br>**Between-subjects design** |
| **Van Koningsbruggen et al. (2014) Study 1** | N: 46 (24 ICT) | Mean age: 21.76 years<br>53.9% Females | Go/No-Go task<br>Sweets and neutral images<br>ICT: inhibit to sweet (100% contingency) images and respond to neutral images<br>Control: respond to sweet images and inhibit to neutral (100% contingency) images<br>72 trials: 12 critical<br>Average successful inhibition = 99.33%<br>Mean BMI: 22.08<br>Between-subjects design | **Operant: Computerised snack dispenser (mean number of sweets)**<br>**Mean BMI: 22.08**<br>**Between-subjects design** |
| **Van Koningsbruggen et al. (2014) Study 2** | N: 46 (24 ICT) | Mean age: 21.17 years<br>62.5% Females | Go/No-Go task<br>Sweets and neutral images<br>ICT: inhibit to sweet (100% contingency) images and respond to neutral images<br>Control: respond to sweet images and inhibit to neutral (100% contingency) images<br>72 trials: 12 critical<br>Average successful inhibition = 99.67%<br>Mean BMI: 21.63<br>Between-subjects design | **Operant: Sweets self-served (grams). This was analysed using z-scores**<br>**Mean BMI: 21.63**<br>**Between-subjects design** |
| **Veling et al. (2011) Study 2** | N: 46 (23 ICT) | Mean age: 21.15 years<br>60.87% Females | Go/No-Go task<br>Sweets and neutral images<br>ICT: inhibit to sweet (100% contingency) images and respond to neutral images<br>Control: respond to sweet images and inhibit to neutral (100% contingency) images<br>72 trials: 12 critical<br>Average successful inhibition = 98.38%<br>Mean BMI: 21.54<br>Between-subjects design | **Ad-libitum: Participants received a bag of sweets and had to return it the next day (grams)**<br>**Mean BMI: 21.54**<br>**Between-subjects design** |
| **Veling et al. (2013b) Study 1** | N: 79 (40 ICT) | Mean age: 21.38 years<br>62.03% Females | Snack food and neutral images<br>ICT: inhibit to snack food (100% contingency) images and respond to neutral images<br>Control: respond to snack food images and inhibit to neutral (100% contingency) images<br>96 trials: 32 critical<br>Average successful inhibition = 99.25%<br>Mean BMI: 22.00<br>Between-subjects design | **Operant: Participants asked to choose foods they would like to take home or eat (number of unhealthy food choices)**<br>**Mean BMI: 22.00**<br>**Between-subjects design** |

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was conducted in RevMan version 5.3 (Cochrane Informatics & Knowledge Management Department, UK, 2014). SMDs were used due to the variability in measurement across different outcome measures. The SMD quantifies the size of the intervention effect in each study relative to the variability observed in that study. For studies that included a within-subjects contrast, we considered within-subject subject correlations in the calculation of the standard error of the SMD (Elbourne et al., 2002). Interpretation of SMD is as follows: 0.2 is indicative of a small effect, 0.5 a moderate effect and 0.8 a large effect (Higgins & Green, 2011). In this case, a positive SMD would indicate a reduction in appetitive behaviour in the ICT group or condition relative to the control group or condition. The $I^2$ statistic was used to assess between-study heterogeneity or variability in effect sizes among studies. $I^2$ was calculated as $I^2 = (Q - df/Q) 	imes 100$, where $Q$ is the chisquared statistic and $df$ is its degrees of freedom. Given variability in study designs and medium-to-high heterogeneity between studies we opted for random effects models (Higgins & Green, 2011), which are more conservative than fixed-effects models and generate wider confidence intervals (Riley, Higgins, & Deeks, 2011).

### 2.6. Studies included in analyses

The majority of studies identified in the searches included one ICT condition and one control condition, and thus each contributed one comparison to the analysis. All studies evaluated the effect of a single session of ICT administered in a laboratory setting. Some studies reported an immediate measure of appetitive behaviour in addition to another measure at follow-up (e.g. Houben, Nederkoorn, Wiers, & Jansen, 2011; Jones & Field, 2013); in these cases we analysed immediate behavioural outcomes only because the effects of ICT on behaviour at follow-up are reported elsewhere (Allom et al., 2015). Werthmann, Field, Roefs, Nederkoorn, and Jansen (2014) provided a measure of ad-libitum consumption and also a measure of search time for chocolate, for this study only ad-libitum consumption was included in analyses. We used total calories or grams consumed for studies that presented more than one type of food during the ad-libitum taste test (Adams, 2014; Lawrence et al., 2015). Some studies (Houben & Jansen, 2011; Jones & Field, 2013; Lawrence et al., 2015) contained more than one control condition, and in these cases we selected the control condition with the fewest trials in which appetitive cues were associated with the requirement to inhibit responding. Four articles investigated the moderating role of individual differences such as dietary restraint or appetite (Houben et al., 2011), and we included two additional studies (Houben, Havermans, Nederkoorn, & Jansen, 2012; Veling, Aarts, & Stroebe, 2013b) that examined the effects of ICT on devaluation but either did not measure immediate appetitive behaviour (Houben et al., 2012) or used a within-subjects design (Veling et al., 2013a), and thus could not be included in the main analysis.

### 2.7. Additional analyses

#### 2.7.1. Stimulus devaluation

Four studies included a measure of appetitive stimulus devaluation (Adams, 2014; Bowley et al., 2013; Di Lemma, in preparation; Houben et al., 2011), and we included two additional studies (Houben, Havermans, Nederkoorn, & Jansen, 2012; Veling, Aarts, & Stroebe, 2013a) that examined the effects of ICT on devaluation but neither of these individual differences and analysed data from the whole sample. We used subgroup analyses to distinguish the effects of ICT on food and alcohol consumption/choice, and to compare the effects of different types of ICT training tasks (Stop Signal, Go/No-Go, and Antisaccade).

#### 2.7.2. Comparison to other psychological interventions

We included data from three articles (four studies) that included psychological interventions as a comparison group in order to examine any differences between ICT and other interventions (Bowley et al., 2013; Di Lemma, in preparation; Van Koningsbruggen et al., 2014).

#### 2.7.3. Moderation by individual differences

We included data from three articles (four studies) that examined the effects of restraint (dietary restraint or current dieting) on ICT effects for food intake (Houben & Jansen, 2011; Lawrence et al., 2015; Veling et al., 2011). We were unable to perform a comparable study.
Fig. 2. Forest plot of the comparisons of the effect of inhibitory control training on appetitive behaviour change, in the laboratory.

Fig. 3. Forest plot of comparisons of the effect of inhibitory control training separately for type of task implemented.
analysis on the alcohol studies because none of the existing studies investigated moderation of effects by attempts to restrict alcohol intake.

Supplementary Table 1 provides a summary of the studies that were included in these subgroup and secondary analyses.

3. Results

Details of the article selection process are shown in Fig. 1. Forty-two full-text articles were excluded for one or more of the following reasons: study did not have a relevant control condition, study did not have a behavioural outcome, ICT did not involve pairings between inhibitory control and appetitive cues, or article did not report results (e.g. study protocols). There were no disagreements regarding exclusion of articles. Details of individual studies are shown in Table 1; note that the majority of studies were conducted in young females.

3.1. The effects of ICT on immediate food or alcohol intake/choice (see Fig. 2)

Eighteen effect sizes from ten published and four unpublished articles were entered into the meta-analysis. The overall difference between ICT and control was statistically significant (SMD = 0.36, 95% CIs [0.24, 0.47]; Z = 6.18, p < .001; I² = 71%) and there was no difference between studies that investigated alcohol-related (k = 5) or food-related behaviour (k = 13; χ² = 0.96, p = .33). The difference between ICT and control groups was significant for both alcohol-related behaviour (SMD = 0.43, 95% CIs [0.30, 0.56]; Z = 6.46, p < .001; I² = 11%) and food-related behaviour (SMD = 0.33, 95% CIs [0.19, 0.47]; Z = 4.57, p < .001; I² = 76%). These results suggest ICT leads to reduced consumption of, or choice for, food and alcohol in the laboratory.

3.2. Effects of different ICT paradigms, and motor versus oculomotor training (see Fig. 3)

We stratified studies based on the type of ICT task used: Stop Signal (k = 5), Go/No-Go (k = 1) and Antisaccade (k = 2). The test for subgroup differences was statistically significant (χ² = 9.43, p = .01). A significant difference between ICT and control groups was observed in studies that used a Go/No-Go task (SMD = 0.47, 95% CIs [0.39, 0.56]; Z = 11.06, p < .001; I² = 0%), but the difference only approached statistical significance in studies that used a Stop Signal task (SMD = 0.23, 95% CIs [-0.00, 0.46]; Z = 1.95, p = .05; I² = 82%), and it was not significant for studies that used an Antisaccade task (SMD = 0.12, 95% CIs [-0.14, 0.38]; Z = 0.92, p = .36; I² = 47%).

3.3. Associatively mediated inhibition: is the number of cue-inhibition pairings important?

We performed random effects meta-regressions in SPSS to investigate if the ICT effect size was influenced by (1) the number of cue-specific inhibition trials (or ‘critical’ trials), (2) the contingency between appetitive cues and the requirement to inhibit and (3) the degree to which participants were able to successfully inhibit responding on critical trials. There was considerable variability in the number of cue-specific inhibition trials (minimum 12, maximum 216, mean = 88.72), but this was not predictive of the ICT effect size (coefficient = -0.001, SE = 0.001, 95% CIs [-0.003, 0.002], p = .82). There was less variability in the contingency between appetitive cues and the requirement to inhibit (minimum 80%, maximum 100%, mean 95.08%), and this was also not predictive of the ICT effect size (coefficient = 0.015, SE = 0.009, 95% CIs [-0.002, 0.033], p = .10). However, variation in the proportion of successful inhibitions on critical trials (minimum 66.15%, maximum 99.67%, mean 89.82%) was a significant predictor of the ICT effect size (coefficient = 0.013, SE = 0.005, 95% CIs [0.004, 0.022], p < .01). The ICT effect size was smaller in studies in which participants failed to inhibit responding to appetitive cues.

3.4. Does ICT lead to stimulus devaluation?

Six studies investigated stimulus devaluation after ICT using variants of the Implicit Association Task (IAT; five studies) or likert scales (one study). Four studies used a pre-post design in which participants completed the IAT immediately before and immediately after ICT; for these studies, within-subject comparisons (pre manipulation vs. post manipulation) were entered into the meta-analysis. One study administered the IAT only once, immediately after ICT, and in this case we analysed the between-group effect. One study examined stimulus devaluation across a range of stimulus – stop pairings (4, 12, or 24); for this we averaged the effect of ICT (‘No-Go’) versus control (‘Go’) conditions across the number of pairings. Stimulus devaluation after ICT was not significantly different between ICT and control groups (SMD = 0.06, 95% CIs [0.16, 0.27]; Z = 0.52, p = .60, I² = 64%). Therefore, repeated inhibition of behaviour in response to appetitive stimuli does not appear to lead to devaluation of those stimuli, although it is important to highlight that the majority of the studies included in this analysis used the IAT to measure stimulus devaluation.

3.5. Comparison of ICT with different psychological interventions

Four studies compared ICT to a different psychological intervention. Two studies (reported in one paper) compared ICT to one session of implementation intentions (Gollwitzer & Sheeran, 2006), one study compared ICT to cue avoidance training (Wiers, Eberl, Rinck, Becker, & Lindenmeyer, 2011), and another study compared ICT to a brief intervention for heavy drinkers (Kyproi et al., 2009). We contrast the effects of ICT and these interventions on appetitive behaviour in the laboratory, with a positive SMD indicative of a larger effect for ICT versus other interventions. The difference between ICT and other psychological interventions was not statistically significant (SMD = 0.06, 95% CIs [-0.08, 0.20]; Z = 0.86, p = .39, I² = 0%), which suggests that ICT is equally as effective as other interventions for changing appetitive behaviour in the laboratory.

3.6. The moderating role of restraint

Four studies examined the potential moderating role of individual differences in attempts to restrict food intake (as inferred from dieting status or restraint) on effects of ICT on behaviour. We contrasted food intake in ICT vs. control groups separately for subgroups with high vs. low self-reported attempts to restrict food intake. In high restriction groups there was a significant effect of ICT on food intake (SMD = 0.50, 95% CIs [0.11 – 0.90]; Z = 2.48, p = .01, I² = 62%). In low restriction groups the effect of ICT was not significant (SMD = –0.18, 95% CIs [–0.85 – 0.59]; Z = 0.53, p = .59, I² = 83%). However, the test for subgroup differences was not statistically significant (χ² = 2.99, p = .08).

3.7. Evidence of publication bias (Supplementary Fig. 1)

Visual examination of a funnel plot suggested reasonable symmetry. We also performed Egger’s test of publication bias by regressing the Standard Normal Deviate (the Standard Mean
Difference divided by its standard error) against the estimate’s precision (the inverse of the SE; Egger, Smith, Schneider, & Minder, 1997) on the fourteen published effect sizes examining immediate behaviour change. Egger’s test was not significant (t(13) = -0.38, p = .71) suggesting no formal evidence of publication bias.

We also performed a trim and fill analysis (Duval & Tweedie, 2000) on the 18 effect sizes examining behaviour change (including the four unpublished studies), using Stata (Statacorp, 2011). This analysis suggests that small studies may have inflated the calculated effect size: The adjusted analysis reduced the magnitude of the overall ICT effect (SMD = 0.24, 95% CI [0.13, 0.36]; Z = 4.12, p < .01). However, care must be taken when interpreting adjusted effect sizes with high between-study heterogeneity (Peters, Sutton, Jones, Abrams, & Rushton, 2007), as was the case here.

4. Discussion

Our meta-analysis demonstrated that a single session of ICT leads to a robust reduction in food and alcohol consumption in the laboratory. The overall effect size was small, with moderate-to-high heterogeneity across studies. The effect of ICT on behaviour was dependent on the task used: the effect was robust when modified Go/No-Go tasks were used, was marginally significant when Stop Signal tasks were used, but was not significant when Antisaccade tasks were used. The effect of ICT was not moderated by the type of appetitive behaviour (alcohol or food intake). Meta-regression analyses revealed that the ICT effect size could not be predicted by either the absolute number of cue-inhibition pairings, or the contingency between appetitive cues and the requirement to inhibit. However, the proportion of successful inhibitions to appetitive cues was a significant predictor of the ICT effect size. We also demonstrated that the effect of ICT on implicit evaluations of appetitive cues did not appear to be robust, that the effect of ICT on behaviour was comparable to that produced by other psychological interventions, and that ICT may be more effective in individuals attempting to restrict food intake.

We tested theoretical predictions that ICT influences behaviour because it leads to the formation of associations between appetitive cues and inhibition of behaviour (associatively-mediated inhibition; McLaren & Verbruggen, in press; Verbruggen & Logan, 2008, 2009; Verbruggen, McLaren, et al., 2014). Some findings from previous studies are consistent with this claim, for example slowing of reaction times and/or a reduction in the number of inhibition errors in response to appetitive stimuli as ICT progresses (Jones & Field, 2013; Lawrence et al., 2015; but see Houben et al., 2012), motor slowing to an action probe following stimuli associated with inhibition (Veling et al., 2011), and stronger implicit associations between food and stopping after ICT (Houben & Jansen, 2015). Our meta-regression analyses revealed no significant relationship between the absolute number of critical trials (in which participants had to exercise inhibition in the presence of an appetitive cue) and the magnitude of the effect of ICT on subsequent behaviour. This finding is consistent with one study which demonstrated that the number of stimulus no-go pairings (4, 12, or 24 pairings) did not moderate the effect of ICT on devaluation of food cues (Veling et al., 2013a). We also observed that the ICT effect size was unrelated to the contingency between appetitive cues and the requirement to inhibit.

However, another meta-regression analysis demonstrated that the proportion of successful inhibitions plays an important role: the effects of ICT on behaviour were diminished in proportion to the number of inhibition failures during critical trials. Our interpretation is that, in order for ICT to influence appetitive behaviour, it is essential that participants learn to associate appetitive cues with inhibition of behaviour rather than with signals that inhibition is required (stop signals or no-go cues), as is predicted by theories of associative inhibition (McLaren & Verbruggen, in press; Verbruggen & Logan, 2008, 2009; Verbruggen, McLaren, et al., 2014). It is important to note that the contingency between appetitive cues and the requirement to inhibit also approached statistical significance (p = .10) as a predictor of the ICT effect size, and there was a strong positive correlation between this contingency and the proportion of successful inhibitions on critical trials (r = 0.62, p < .01). Inspection of Table 1 confirms that as this contingency approached 100%, the rate of inhibition errors approached zero. This explanation may partially account for the larger and more statistically robust ICT effect size when Go/No-Go rather than Stop-Signal or Antisaccade tasks were used for ICT, because the cue-inhibition contingency tended to be much higher in the Go/No-Go studies compared to the other studies (see Table 1). Further research is required to investigate if the higher cue-inhibition contingency and/or the training of action restraint, rather than action cancellation, is responsible for the superior effectiveness of Go/No-Go ICT. This issue could be investigated by comparing behavioural effects of ICT after Go/No-Go and Stop Signal tasks with differing cue-inhibition contingencies. Perhaps related, our stratified analysis demonstrated that the type of behaviour that is inhibited during ICT may be important, because the ICT effect size appeared robust in studies that targeted motor inhibition (Go/No-Go and Stop-Signal) but it was not statistically significant in the two studies that used an Antisaccade task to target oculomotor inhibition. One explanation is that both Go/No-Go and Stop Signal tasks require the suppression of activity in effector muscles that are used to interact with and consume food and alcohol (c.f. Freeman, Razhas, & Aron, 2014), whereas Antisaccade tasks require the suppression of oculomotor responses that are not directly required for food or alcohol consumption. Further ICT studies that use a modified Antisaccade task are required in order to investigate if the distinction between training of motor and oculomotor inhibition is an important one.

We performed additional analyses to test the theoretical claim that appetitive cues would become devalued after being paired with inhibition of behaviour (Veling et al., 2008). Some studies that used a modified Go/No-Go task demonstrated that ICT led to devaluation of appetitive cues that had been paired with inhibition, and this effect mediated the effects of ICT on behaviour change (Houben et al., 2012, 2011; Veling et al. 2013a). However, our meta-analysis of these and other studies (some of which are currently unpublished) failed to detect an overall effect of ICT on stimulus devaluation. The majority of these studies measured devaluation using an implicit association test (IAT), yet other studies demonstrated devaluation effects following ICT for a range of stimuli when using Likert scales (Ferre, Frischen, & Fenske, 2012; Lawrence, O’Sullivan et al., 2015b; Veling et al., 2008) or willingness to pay paradigms (Wessel et al., 2014). These contrasting findings may be explained by the general weak relationships between implicit and explicit measures of stimulus evaluation (c.f. Friese, Hofmann, & Wanke, 2008). Our conclusion is that there is no robust effect of ICT on stimulus devaluation remains tentative and requires further investigation, for example by including Likert scales after ICT to test the stimulus devaluation account.

Our additional analyses suggested that the effects of ICT on food intake were moderated by individual differences in attempts to restrict eating behaviour, with the largest effects seen in people who were currently dieting or had high levels of dietary restraint. There are several plausible explanations for this moderation effect, all of which warrant further investigation. Strong motivation to
change behaviour may facilitate the learning of cue-inhibition associations during ICT due to concordance between the goal to restrict food intake, and task contingencies that favour inhibition of motor responses to food cues. Alternatively, high levels of dietary restraint may be associated with strong appetitive responses to food cues (Houben, Roefs, & Jansen, 2010; Johnson, Pratt, & Wardle, 2012); given that the effects of ICT on behaviour may be proportional to the strength of appetitive responses to cues before ICT (Veling et al., 2013b; Freeman et al., 2014), one might expect ICT effects for food cues to be more pronounced in restrained eaters. We urge caution in interpretation of our findings because the test for subgroup differences was not statistically significant, probably partly because of the small number of studies (4) that investigated individual differences as moderators of ICT effects. Nevertheless, this is a promising avenue for future research, and it is also important to extend this line of inquiry to ICT for problem drinking by investigating whether individual differences in attempts to limit drinking moderate the effects of ICT on alcohol intake.

ICT studies tended to employ a control group (or condition) in which the stimulus-inhibition contingencies were reversed compared to those in operation for the ICT group(s). That is, participants in most control groups were required to rapidly respond to appetitive stimuli and inhibit responses to neutral stimuli. This is problematic given that the subjective value of food-related images can be increased by asking participants to repeatedly respond to those images (Schonberg et al., 2014); therefore, the effect size for ICT may be inflated or even driven by these control groups. However, this explanation appears unlikely for several reasons. First, two studies (Jones & Field, 2013; Lawrence et al., 2015), addressed this issue by incorporating ‘ignore signal’ control conditions in which participants responded to both appetitive and control cues without inhibition. In these studies, contrasts between ICT and the ‘ignore signal’ control conditions were suggestive of reduced food or alcohol consumption following ICT, although the findings were not clear-cut. Second, two studies demonstrated weight loss following ICT compared to a general inhibition training manipulation that involved no exposure to food cues (Lawrence et al., 2015b; Veling, van Koningsbruggen, Aarts, & Stroebbe, 2014). Finally, our analyses demonstrated that effects of ICT on behaviour were comparative to those produced by other, more well-established psychological interventions including implementation intentions (Gollwitzer & Sheeran, 2006), avoidance training (Wiers et al., 2011) and a brief intervention for problem drinking (Kypri et al., 2009). Further work is required to confirm that ICT leads to reduced appetitive behaviour relative to a more appropriate active control intervention (i.e. neutral ‘go’, or general inhibition conditions c.f. Jones et al., 2011; Lawrence et al., 2015), and it will also be important to ensure that participants’ expectations of behaviour change are matched across ICT and control groups (Boot, Simons, Stothart, & Stutts, 2013).

To date, the majority of ICT studies have been conducted on healthy young adults, mostly female college students. Caution is required before generalising these findings to other populations, and in particular there is an urgent need to investigate the effectiveness of ICT in individuals who may benefit from it, such as patients with alcohol use disorders and obese patients who are attempting to lose weight. The observation that ICT can lead to behaviour change after minimal training (see above) may increase its acceptability and participants’ engagement with it if it were eventually to be offered as a behavioural intervention. Perhaps unsurprisingly, the effects of a single session of ICT may not persist over time (see Allom et al., 2015; Jones & Field, 2013), and three recent studies (not included in our meta-analysis) yielded mixed but encouraging findings regarding the effects of repeated ICT sessions delivered over the internet on weight loss (Allom & Mullan, 2015; Lawrence et al., 2015b; Veling et al., 2014). We note that randomised controlled trials investigating the effectiveness of multiple sessions of ICT for the reduction of heavy drinking in problem drinkers are currently in progress (Jones et al., 2014; Van Deursen, Salemink, Smit, Kramer, & Wiers, 2013).

5. Conclusions

The meta-analysis presented here confirmed the effect of ICT on reducing appetitive behaviours (food and alcohol consumption/choice) in the laboratory. We demonstrated that these effects were larger for Go/No-Go rather than other tasks, were moderated by attempts to restrict calorie intake, and were comparable to effects produced by other psychological interventions. We observed that the extent of successful inhibition in response to appetitive cues was a significant predictor of the effect of ICT on behaviour, which suggests that the formation of stimulus-inhibition associations is critical if ICT is to influence behaviour. Further research is required to clarify the mechanisms of action of ICT, and we await the results from randomised controlled trials investigating the effectiveness of multiple sessions of ICT in participants who are attempting to reduce their food intake or alcohol consumption.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.appet.2015.11.013.

Conflict of interest

All authors declare no conflicts of interest.

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