Is impulsivity related to attentional bias in cigarette smokers? An exploration across levels of nicotine dependency and deprivation.

Running head - Attentional bias and impulsivity.

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Abstract

Research has largely focused on how attentional bias to smoking-related cues and impulsivity independently influence the development and maintenance of cigarette smoking, with limited exploration of the relationship between these mechanisms. The current experiments systematically assessed relationships between multiple dimensions of impulsivity and attentional bias, at different stages of attention, in smokers varying in nicotine dependency and deprivation. Non-smokers (NS; n=26), light satiated smokers (LS; n=25), heavy satiated smokers (HS; n=23) and heavy 12-hour deprived smokers (HD; n=30) completed the Barratt Impulsivity Scale, Delayed Discounting Task, Stop-Signal Task, Information Sampling Task and a Visual Dot-Probe assessing initial orientation (200ms) and sustained attention (2000ms) towards smoking-related cues. Sustained attention to smoking-related cues was present in both HS and LS, whilst initial orientation bias was only evident in HS. HS and LS also had greater levels of trait motor and non-planning impulsivity and heightened impulsive choice on the delay discounting task compared to NS, while heightened trait attentional impulsivity was only found in HS. In contrast, in HD, nicotine withdrawal was associated with no attentional bias, but heightened reflection impulsivity, poorer inhibitory control and significantly lower levels of impulsive choice relative to satiated smokers. Trait and behavioural impulsivity were not related to the extent of attentional bias to smoking-related cues at any stage of attention, level of nicotine dependency or state of deprivation. Findings have both clinical and theoretical implications, highlighting the unique and independent roles impulsivity and attentional bias may play at different stages of the nicotine addiction cycle.

Keywords

Attentional bias, trait impulsivity, behavioural impulsivity, smoking, nicotine, deprivation, dependence

Introduction

Smoking-related attentional bias and impulsivity have been identified as key risk factors for the development and maintenance of cigarette smoking, but despite theoretical predictions and important treatment implications, their relationship has rarely been explored. Biased attentional processing of smoking-related cues has been argued to result from repeated drug use sensitising the mesolimbic dopamine pathway, causing both the drug itself and cues paired with the drug, to acquire strong motivational properties, becoming more salient and 'wanted' by the drug user (e.g. Robinson and Berridge, 1993; 2001). As the salience of cues increases, they become the focus of attention, highly craved, and more able to elicit drug-seeking and taking behaviour. Theoretically, the salience and motivational properties of drug-related cues that drive attentional bias should be particularly enhanced in more impulsive individuals (e.g. Jentsch and Taylor, 1999; Dawe, et al., 2004; Field and Cox, 2008; Coskunpinar and Cyders, 2013); a proposal supported by findings that impulsivity enhances classical conditioning (e.g. Settles et al., 2010; 2014; Smith et al., 2006), and shares elements of underlying neurobiology with attentional bias (Coskunpinar and Cyders, 2013). Despite the expectation these risk factors are related, research to date has largely considered them independently.

It is well established that cigarette smokers display an attentional bias towards smoking-related cues (e.g. Mogg and Bradley, 2002; Waters et al., 2003; Bradley et al., 2004; Drobes et al 2006; Correa and Brandon 2016), although the relationship between bias and levels of nicotine dependence and deprivation remains unclear. For example, higher nicotine dependence and/or frequency of smoking have been associated with both greater (e.g. Zack et al., 2001; Mogg and Bradley 2002; Vollstadt-Klein et al., 2011; Larsen et al., 2014; Elfeddali et al., 2016) and reduced levels of attentional bias (e.g Hogarth, et al., 2003; Waters et al., 2003; Yan et al., 2009; Rehme et al., 2018). Relative to non-deprived smokers, smokers in nicotine withdrawal have also shown evidence of both greater (e.g. Gross et al., 1993; Waters and Feyerabend, 2000; Leventhal et al., 2008; Canamar and London, 2012) and no change in bias (Mogg and Bradley, 2002, Munfano et al., 2003; Dawkins et al., 2006; Hendricks et al., 2006). One reason for these inconsistencies could be that paradigms across studies have captured different stages of attention; and bias manifests differently across these stages, for different smokers. Supporting this possibility, research examining bias at distinct stages has revealed that whilst high and low dependent smokers are comparable in their initial orientation towards smoking cues, less dependent smokers exhibit greater maintenance of attention (Mogg et al., 2005). Nicotine deprivation has also been shown to enhance dwell time compared to when satiated, in the absence of changes in biased initial fixation (Field et al., 2004).

Impulsivity has also been found to play a critical role in the development and maintenance of, and relapse to, cigarette smoking, acting as both a risk factor and consequence of use (e.g. Mitchell, 2004; VanderVeen et al., 2008; de Wit, 2009; Bloom et al., 2014). A multidimensional construct defined as the predisposition toward rapid, unplanned reactions to internal or external stimuli without regard for the negative consequences (Moeller et al., 2001), impulsivity can be assessed as a relatively stable 'trait' through self-report measures and as a fluctuating behaviour using behavioural laboratory tasks. Compared to non-smokers, cigarette users display heightened trait impulsivity (e.g. Reynolds et al., 2007; Field et al., 2009; Durazzo et al., 2016; Bos et al., 2019) impulsive choice (e.g. Bickel et al., 1999; Mitchell, 1999; Reynolds, 2006; Reynolds and Fields, 2012; Pope et al., 2019) and reflection impulsivity (Round et al., 2020), although evidence of poorer inhibitory control has not been consistently found (e.g. Dinn et al., 2004; Carim-Todd et al., 2016; Yin et al., 2016; Detandt et al., 2017; Wilcockson et al., 2021). Critically, however, heavier, more dependent smoking is associated with both reduced inhibitory control (Spinella, 2002; Billieux et al., 2010) and greater levels of impulsive choice (Reynolds, 2004; Heyman and Gibb, 2006; Stillwell and Tunney, 2012). Nicotine deprivation has also been shown to result in poorer inhibitory control (e.g. Mendrek et al., 2006; Dawkins et al., 2007; Harrison et al., 2009; Charles-Walsh et al., 2014; Tsaur et al., 2015; Kalhan et al., 2022), while short-term withdrawal has been found to both heighten (Field et al., 2006; Yi and Landes, 2012; McCarthey et al., 2018) and have no effect (Mitchell, 2004; Roewer et al., 2015) on levels of impulsive choice, with no evidence yet available for the impact of deprivation on reflection impulsivity. These findings suggest different dimensions of impulsivity may contribute to smoking maintenance during different stages of addiction, and particularly highlight the need for more evidence to evaluate the role of reflection impulsivity.

Despite accumulating evidence of an influential role for both attentional bias and impulsivity in cigarette smoking, there is minimal understanding of how these constructs relate to each other. Two meta-analyses (Coskunpinar and Cyders, 2013; Leung et al., 2017) exploring associations between attentional bias to a range of different substances (e.g. food, drugs, alcohol, and tobacco) and dimensions of impulsivity suggest a small positive association may exist. Analyses indicated no evidence of moderation by type of substance or dimension of impulsivity, although there was some indication that behavioural impulsivity may, overall, relate more strongly than trait impulsivity, to attentional bias (Coskunpinar and Cyders, 2013). Importantly however, the meta-analyses did not evaluate bias-impulsivity relationships at different stages of attention, with most studies reviewed adopting measures that were either ambiguous in terms of the stage of attention they captured or focused on maintained attention. Furthermore, only two studies within the analysis examined tobacco-related attentional bias (Field et al., 2007; Powell at el., 2010), limiting the implications of these results for cigarette smokers.

A limited number of studies have since examined relationships between trait impulsivity and attentional bias at both initial orientation and later stages of attention in smokers. For example, using a range of cue exposures in a visual dot probe (VDP), dimensions of trait impulsivity only predicted bias to smoking cues presented for 400ms in young adult smokers (Perlato et al. 2014). However, firm conclusions are hard to draw from these results, as the 400ms cue exposure duration falls between the length argued to represent initial orientation (200ms or below) and the length argued to better capture maintenance of attention (over 500ms) (e.g. Field and Cox, 2008). Using less ambiguous cue exposure durations, Della Libera et al. (2019) in a group of more dependent treatment-seeking smokers, found higher trait impulsivity was a predictor of both initial orientation (100ms) and maintenance of attention (800ms) towards smoking cues.

Taken together, these findings suggest that higher trait impulsivity may indeed be associated with the development of stronger attentional biases to smoking-related cues. Despite the potential clinical implications of this relationship for interventions that aim to promote abstinence, our understanding of it remains in its infancy. The precise nature of the relationship across different stages of attention may vary between different types of smokers (e.g. Perlato et al., 2014; Della Libera et al., 2019), and to date only a single trait measure of impulsivity has been explored, meaning simultaneous assessment of multiple dimensions of trait and behavioural impulsivity is important, to reveal any unique relationships. The present study was designed to provide a more comprehensive investigation of the relationship between impulsivity and attentional bias to smoking-related cues in cigarette smokers. A sample of non-smokers, light smokers, heavy satiated, and heavy deprived smokers were recruited to i) determine whether impulsivity and attentional bias differed according to level of dependence severity and nicotine deprivation and, ii) explore the association between impulsivity and attentional bias across levels of dependency and deprivation. The Barratt Impulsivity Scale (BIS-11) was used to assess trait impulsivity and the Delay Discounting Task (DDT), Stop-signal Task (SST) and Information Sampling Task (IST) were used to assess behavioural dimensions of impulsive choice, inhibitory control and reflection impulsivity, respectively. The inclusion of the IST was of particular importance given the limited attention reflection impulsivity has received in smokers to date. Attentional bias was assessed using a VDP where stimuli were presented for 200 and 2000ms to enable examination of initial orientation and maintenance of attention. Overall, it was hypothesised that higher levels of impulsivity and attentional bias would be present in heavier and nicotine deprived smokers, and that impulsivity would be positively associated with smoking-related bias.

Method

Participants

Non-smokers (NS; n = 26), light satiated smokers (LS; n = 25), heavy satiated smokers (HS; n = 23) and heavy 12-hour nicotine deprived smokers (HD; n = 30) were recruited (see Table 1). Heavy smokers had smoked at least 10 cigarettes per day for one year and light smokers, between one and five cigarettes per day. Non-smokers reported never having smoked a cigarette. Participants were aged between 18 and 60, reported no psychiatric illness or other drug dependencies, had English as their first language, and visual acuity within normal limits. Most were staff and students at the University of Leeds and Leeds Beckett University (LBU); others were recruited from Gumtree and businesses in Leeds. All participants gave written, informed consent and were compensated for their time. The study was approved by LBU Psychology ethics committee (approval reference - 12-0003).

Materials

Fagerstrom Test for Nicotine Dependence (FTND). The six-item FTND (Heatherton, et al., 1991) assessed severity of nicotine dependence, with higher scores reflecting greater dependence.

Trait Impulsivity Measure

Barratt Impulsiveness Scale (BIS-11). Trait impulsivity was assessed using the BIS-11 (Patton et al., 1995), a 30-item self-report measure containing three distinct sub-scales: motor impulsiveness (e.g. “I act on the spur of the moment”), attentional impulsiveness (e.g. “I can only think about one thing at a time”) and non-planning impulsiveness (e.g. “I plan tasks carefully). Higher scores indicated greater levels of impulsiveness. Cronbach’s alphas ranged from .71-.86.

Behavioural Impulsivity Measures

Delay Discounting Task (DDT). Impulsive choice was measured using a hypothetical monetary DDT, programmed in Microsoft Visual Basic® 6.0 (Johnson and Bickel, 2002), where participants were instructed to make their choices as if rewards were real.

Two large command buttons were displayed containing two different sums of money, one on the left and one on the right of the screen. On each trial participants chose, via a mouse click, between an immediate smaller reward of varying size and a larger set reward of £1000 available after a delay. The magnitude of the immediate reward varied until a point of indifference was reached at that delay. The delay to receiving the reward varied, with trials presented in blocks from smallest (1 day) to largest (25 years) delays. Indifference points were determined for seven delays: 1 day, 1 week, 1 month, 6 months, 1 year, 5 years and 25 years. To determine the level of delay discounting the area under the curve (AUC) was calculated following Myerson et al. (2001), with smaller values indicating higher levels of discounting.

Stop Signal Task (SST) Inhibitory control was measured using an SST (Verbruggen et al., 2008). Participants were asked to respond as fast and accurately as possible to either a white circle or square (primary stimulus) presented centrally for 1250ms on a black background by pressing the right (to identify a circle) or left (to identify a square) arrow keys accordingly (Go trial). On 25% of trials, stimuli were followed by an auditory stop signal (bleep) lasting 75ms, indicating participants must withhold their response (STOP trial). There was a practice block of 32 trials followed by four blocks of 64 trials. Each trial started with a fixation cross, followed by the primary stimuli after 250ms. The inter-trial interval was 2000ms. Stop signal delay (SSD; the delay between the onset of the primary stimulus and the auditory stop signal) varied based on the participants' behaviour following a staircase algorithm procedure, until a delay was determined at which participants were able to successfully stop on 50% of the STOP trials. There was a 10 sec delay between blocks, during which participants received feedback on their performance on the previous block.

Reaction times and accuracy on both Go (Mean GO Trial RT; Mean % Correct Responses on No-Signal Trials; Mean % Missed Response on No-Signal Trials) and STOP trials (Mean STOP Trial RT; Mean % Responding on STOP Trials) were recorded. The main index of response inhibition was the time required to inhibit a response following a STOP signal, the stop-signal reaction time (SSRT). The SSRT was calculated by subtracting the SSD from the mean reaction times on Go trials. Longer SSRTs indicate poorer response inhibition. Participants who failed to successfully inhibit their responses on 50% of STOP trials or failed to respond on more than 10% of Go trials were excluded from the analysis.

Information Sampling Task (IST). Reflection impulsivity was measured using the IST (Clark et al., 2006). Participants were presented with a 5x5 matrix of grey squares, each of which covered a red or blue box. On each trial, participants clicked (with the mouse) to open as many boxes as they wished, before making a decision about which colour lay in the majority, by clicking to choose between a red and blue panel that were presented at the bottom of the screen. Once opened, the box colour remained visible for the remainder of that trial. A practice trial was followed by two task conditions (counterbalanced across participants) with 10 trials in each. In the ‘fixed win’ condition (FW) participants gained 100 points for a correct decision, irrespective of the number of boxes opened, and lost 100 points for an incorrect decision. In the ‘decreasing win’ condition (DW) participants began with 250 points at the start of each trial and the amount available to win for a correct response decreased by 10 points for every box opened. Again, for an incorrect decision, 100 points were lost regardless of the number of boxes opened.

In both conditions, feedback about the points won was given at the end of each trial. To discourage delay-averse responding, the inter-trial interval varied from 1 to 30 seconds, depending on how quickly the previous trial was completed. Measures included average number of boxes opened, number of incorrect judgments, total points won and latency of box opening. The main index of reflection impulsivity was the probability of making a correct choice at the point of decision on each trial [P(correct)], which indicated the level of uncertainty tolerated during decision-making. P(correct) was calculated as follows:

P(Correct)= $\frac{\sum_{k=A}^{Z}\binom{Z}{k}}{2^{Z}}$ where Z = 25 - (number of boxes opened), and A = 13 - (number of boxes of the chosen colour). Lower P(correct) scores indicate higher levels of reflection impulsivity.

Attentional Bias

Visual Dot Probe (VDP). Attentional bias was assessed using a VDP task based on Field et al. (2004), programmed and run in E-Prime. The stimuli consisted of 20 colour smoking-related images (e.g. a packet of cigarettes), each paired with a neutral, non-smoking-related image (e.g. a packet of pencils) matched on image complexity, colour saturation and brightness. Twenty-four picture pairs of furniture were used for filler and practice trials. Images were 125mm x 100mm, displayed side-by-side on a black background, with their inner edges 60mm apart. The probe was a white arrow (30 mm high), pointing up or down.

Each trial began with a fixation cross for 500ms, which was replaced by a pair of images displayed for either a short (200ms) or long (2000ms) duration. Immediately after picture offset, the probe replaced one of the images and remained on screen until participants pressed a key to indicate the direction of the arrow. An inter-trial interval of 1000ms followed, during which a black screen was presented. A 16-trial practice block was followed by 160 critical and 80 filler trials. During critical trials, each of the 20 smoking-neutral picture pairs were presented 4 times at each duration (200ms and 2000ms). Each image appeared twice on the right of the screen, and twice on the left, for each duration, and probes replaced neutral and smoking-related images with equal frequency. Probe-to-picture location combination was also balanced for filler trials. The order of trials was randomised for each participant. For each stimulus duration, the reaction times to the probe replacing the neutral and smoking-related stimuli were recorded.

Procedure

Participants were assigned to one of the four smoking groups (NS, LS, HS, HD) with age and gender balanced across groups. Testing took place at the Psychology Laboratories at LBU with participants required to abstain from alcohol for 24 hours prior to the session. Upon arrival, all smokers completed the FTND, and smokers' status and level of nicotine deprivation biochemically verified via a breath sample of carbon monoxide (CO). For nicotine deprived smokers, this was compared against a baseline reading to ensure compliance with abstinence. All participants completed the BIS-11 followed by the SST, DDT and IST, with order of behavioural impulsivity tasks counterbalanced, and then completed the VDP. The session lasted 1 hour, after which participants were debriefed and compensated for their time.

Statistical Analyses

For impulsivity, effects of dependency were assessed by comparing NS, LS and HS on trait and behavioural impulsivity scores via one-way ANOVAs, followed with Tukey's pairwise comparisons, or Games-Howell if homogeneity of variance was violated. For effects of deprivation, HS and HD smokers were compared via independent groups t-tests. Variables violating normality were assessed using Kruskal Wallis or Mann Whitney U tests. To examine attentional bias, mixed ANOVAs were used to compare reactions times in the VDP, with smoking group as between subjects factor (for level of dependency: NS, LS, HS; for level of deprivation: HS and HD), and exposure (200ms, 2000ms) and image type (neutral vs. smoking) as within subject factors. Significant interactions were clarified via simple effect analyses. Trials with errors (3.7% of data) or reaction times less than 200ms or greater than 2000ms were removed.

To explore relationships between attentional bias and impulsivity in smokers, bias scores (reaction time to probes replacing neutral images - reaction time to probes replacing smoking images) were calculated at each exposure duration, with a positive bias score indicating a smoking-related bias. Relationships were examined between BIS-11 ratings, scores for the main indices of impulsivity in the DDT (AUC), SST (SSRT), IST (P(correct)), and attentional bias scores at each exposure duration (200 and 2000ms). To explore these impulsivity-bias relationships and whether they differed across smokers with different levels of dependency, a series of moderated multiple regressions were initially conducted. For each analysis, a single impulsivity measure, dependency group, and their interaction, were entered simultaneously to predict bias score (either at 200 or 2000ms). Following Hayes (2017), in the absence of significant interactions in these moderated models, partial effects were presented; in keeping with the focus of the study and in the interests of parsimony, these are in the form of partial correlations between impulsivity and bias score, while controlling for dependency group. The Larzelere & Mulaik (1977) correction was applied to these correlational analyses, to control the familywise error rate. The equivalent analytical approach was adopted to explore impulsivity-bias relationships, and whether they differed across levels of deprivation, with dependency group being substituted for deprivation group in these analyses.

Results

Analysis across levels of nicotine dependency

Participants' Characteristics

Table 1 summarises the demographics and smoking profiles for all groups. There was no significant difference in gender ratio (χ^2 (2) = .18, *p* = .912, ϕ = .050) or age (*H* (2) = 2.518, *p* = .284; η^2_H = .014) between NS, LS and HS.

HS smoked significantly more cigarettes per day (*t* (24.83) = -10.95, *p* < .001, *d* = 4.10), reported greater levels of dependency (*t* (34.69) = -8.67, *p* < .001, *d* = 2.56), and had higher CO levels (*t* (30.64) = -5.94, *p* < .001, *d* = 1.76) than LS, but the groups had smoked for a comparable number of years (*t* (18.52) = -2.01, *p* = .060, *d* = 0.76).

Trait Impulsivity

Barratt Impulsivity Scale. There was a significant group effect on Total BIS scores (F (2,71) = 13.94, p < .001, η^2 = .28) and each of the subscales: Motor (F (2, 71) = 9.03, p < .001; η^2 = .20); Attention (F (2, 71) = 8.81, p < .001; η^2 = .20); Non-Planning (F (2,71) = 9.90, p < .001, η^2 = .22). For Total BIS, Motor and Non-planning, HS and LS had comparable (all p ≥ .066), but significantly higher scores than NS (all p ≤ .037). In contrast, on the Attention subscale, HS scored significantly higher than both NS (p < .001) and LS (p = .049), who did not differ (p = .173) (See Table 2).

Behavioural Impulsivity

Delay Discounting Task. There were significant group differences on total AUC (F (2, 67) = 9.72, p < .001, η2 = .23), with HS and LS displaying comparable (p = .953) discounting of delayed reward, both significantly greater than the NS (all p = .001) (see Table 2).

Stop Signal Task. No significant group differences were observed on SSRT (F (2,54) = 2.49, p = .093, η2 = .09) (see Table 2 and Supplementary Materials Table 1 for analysis of additional task measures).

Information Sampling Task. No significant group differences were observed on P(correct) during FW (F (2, 71) = .53, p ≥ .591, η^2 = .02), or DW (all (F (2, 71) = .91, p = .407, η^2 = .03) condition trials (see Table 2 and Supplementary Materials Table 1 for analysis of additional task measures).

Attentional Bias

Visual Dot Probe Task. A 2 x 2 x 3 mixed ANOVA indicated significant effects of exposure (F (1, 71) = 14.97, p < .001, η^2 = .17), image (F (1,71) = 5.56, p = .021, η^2 = .07) and an exposure x group interaction (F (2,71) = 4.49, p = .015, η^2 = .11); effects further qualified by a significant three-way interaction (F (2,71) = 8.89, p < .001, η^2 = .20). No significant effects of group (F (1,71) =2.96, p = .058, η^2 = .08), exposure x image or image x group were revealed (all F (2,71) ≤ 1.98, p ≥ .146, η^2 ≤ .05).

A series of 2 x 2 ANOVAs by group were conducted to clarify the three-way interaction. In NS there was a significant exposure x image interaction (F (1,25) = 5.65, p = .025, η2 = .18), in the absence of main effects (all F (1,25) ≤ 4.18, p ≥ .052, η2 ≤ .14). NS were quicker to respond to probes replacing the smoking than the neutral image at 200ms with the opposite pattern at 2000ms. However, the effect of image was not significant at either exposure duration (all p ≥.063). In LS there was a significant exposure x image interaction (F (1, 24) = 9.83, p = .004, η2 = .29) and main effect of exposure (F (1,24) = 35.53, p < .001, η2 = .60), but not image (F (1,24) = 1.96, p = .175, η2 = .08). At 2000ms, LS were significantly quicker to respond to probes replacing the smoking than the neutral images (p = .013), but no significant difference was found at 200ms (p = .993). In contrast, for HS there was a significant main effect of image type (*F* (1, 22) = 7.90, *p* = .010, η^2 = .26) but no main effect of exposure or exposure x image interaction (all *F* (1,22) ≤ 1.77, *p* ≥ .197, $\eta^2 \leq$ .08). HS were significantly quicker to respond to probes replacing smoking than neutral images at both 200 (*p* = .012) and 2000ms (*p* = .019; see Figure 1.).

Relationship between impulsivity and attentional bias in smokers

Level of dependency did not significantly moderate the relationship between any measure of trait or behavioural impulsivity and attentional bias at either 200 or 2000ms exposures. (See Supplementary Materials Tables 2 and 3 for full regression models).

Partial correlations, controlling for level of dependency, also revealed no significant correlations between any measure of impulsivity and bias scores at either 200 or 2000ms exposures (see Table 3).

Analysis across levels of nicotine deprivation

Participants' Characteristics

There was no significant difference in gender ratio (χ^2(1) = .91, *p* = .341, ϕ = .13) or age (*U* = 396.00, *p* = .357, *d* = 0.13) between HS and HD (see Table 1).

HS and HD were comparable on the number of cigarettes smoked per day (*t* (41.96) = .46, *p* = .650, *d* = 0.13), levels of dependency (*t* (51) = 2.00, *p* = .051, *d* = .56), and years smoked (*t* (18.71) = .36, *p*= .723, *d* = 0.13). HS displayed significantly higher levels of CO than HD (*t* (25.38) = 5.68, *p* < .001, *d* = 1.76), indicating they had smoked more recently (see Table 1). The HD group also displayed significantly lower levels of CO following 12-hours of nicotine deprivation (mean = 5.33 (2.61)) than when satiated at baseline (mean =14.83 (6.11); *t* (28) = 10.46, p < .001, d = 1.97).

Trait Impulsivity

Barrett Impulsivity Scale. There were no significant differences between HS and HD on Total BIS-11 or any subscales (all *t* (51) ≤ 1.19, *p* ≥ .238, *d* ≤ .33) (see Table 2).

Behavioural Impulsivity

Delay Discounting Task. HS displayed significantly greater discounting of delayed rewards relative to HD (t (49) = -2.68, p = .010, d = .76) (see Table 2).

Stop Signal Task. HD displayed significantly longer SSRTs, indicative of poorer inhibitory control, relative to HS (t (43) = -2.21, p = .033, d = .68) (See Table 2 and Supplementary Materials Table 4 for analysis of additional task measures).

Information Sampling Task. In comparison to HS, HD made decisions when the probability of being correct was significantly lower during both FW (t (51) = 2.95, p = .005, d = .82) and DW (t (51) = 2.80, p = .007, d = .78) conditions (see Table 2 and Supplementary Materials Table 4 for analysis of additional task measures).

Attentional bias

Visual Dot Probe Task. A 2 x 2 x 2 mixed ANOVA revealed a significant main effect of group (F (1, 51) = 9.31, p = .004, η^2 = .15), which was qualified by a significant image x group interaction (F (1,71) = 5.79, p = .020, η^2 = .10) (see Figure 2a.). HS were significantly quicker to respond to probes replacing the smoking than the neutral images (p =.010), but in HD no differences were found across image type (p = .731). HS were significantly faster than HD to respond to probes replacing both the neutral (p = 0.012) and smoking images (p = .001) (see Figure 2b.), with the difference being significantly greater for the smoking images. No further main effects or interactions were significant (all F (1,51) $\leq$ 3.84, $p \geq$ .056, $\eta^2 \leq$ .070)

Relationship between impulsivity and attentional bias in smokers

Level of deprivation did not significantly moderate the relationship between any measure of trait or behavioural impulsivity and attentional bias at either 200 or 2000ms exposures (See Supplementary Materials Tables 5 and 6 for full regression models).

Partial correlations, controlling for levels of deprivation, revealed no significant correlations between any measure of impulsivity and bias scores at either 200 or 2000ms exposures (see Table 4).

Discussion

To the best of our knowledge, this is the first study to comprehensively examine the relationship between impulsivity and attentional bias in smokers with varying nicotine dependency and deprivation levels. Results demonstrated sustained attention towards smoking-related cues in both heavy and light smokers, whilst initial orientation bias was only evident in heavy smokers. Importantly this attentional preference was not present in lifetime non-smokers, and the smoking-related bias in heavy smokers was found to be restricted to periods of nicotine satiation. Relative to non-smokers, nicotine-satiated heavy and light smokers also displayed greater levels of trait impulsivity and impulsive choice, whilst evidence of poorer inhibitory control and heightened reflection impulsivity was only present in heavy smokers experiencing withdrawal. Contrary to our predictions, trait and behavioural impulsivity were not related to smoking-related attentional bias. Instead, impulsivity and attentional bias appear to operate independently in the maintenance of cigarette smoking, each playing a unique role across different stages of the addiction cycle.

Heavy and light satiated smokers' bias to maintain attention on cues presented for 2000ms is consistent with the suggestion that repeated exposure to nicotine heightens the incentive value of smoking-related cues, increasing their ability to maintain attention (Robinson and Berridge,1993; 2001). However, the rapid capture of attention by smoking cues in the 200ms condition was only observed in the more dependent heavy satiated smokers, consistent with past reports that heavy smokers display a bias in both initial and sustained attention (e.g. Bradley et al., 2004; Lopes et al., 2014; Correa and Brandon, 2016) and that the extent of bias at early stages of attention may be related to dependence severity (Perlato et al., 2014). A more rapid deployment of attention to smoking cues may only emerge following greater and more frequent exposure to nicotine, which may produce more substantial neuroadaptations in mesolimbic dopaminergic pathways, further strengthening the incentive value of the cues.

In contrast to when nicotine satiated, there was no evidence of attentional bias to smoking-related cues in heavy smokers in withdrawal. Instead, deprived smokers displayed significantly slower reaction times to both smoking and neutral images, potentially indicating a more general withdrawal-related disruption in cognitive functioning (e.g. Hughes et al., 1989; Hendrick et al., 2006; Ashare et al., 2014), which may have masked any smoking-related bias. Indeed, eye-tracking measures that do not rely on reaction time, appear more sensitive across a range of deprivation lengths (6-36hrs), with greater gaze duration on smoking-related images more consistently found (e.g. Kwak et al., 2007; Kang et al., 2012), and often in the absence of reaction time bias (Field et al., 2004; Lochbuehler et al., 2018).

Smokers at all levels of dependence were characterised by heightened motor and non-planning impulsivity relative to non-smokers, replicating past research (e.g. Mitchell, 1999; Heyman and Gibb, 2006; Reynolds and Fields, 2012; Durazzo et al., 2016), and consistent with the idea that tendencies to rapid, unpremeditated behaviour may contribute to the risk of initiating smoking. In contrast, heightened attentional impulsivity uniquely characterised the more dependent smokers, supporting suggestions that this dimension of impulsivity may be involved in the escalation of cigarette use and dependency (e.g. Ryan et al., 2013a).

In line with previous research, satiated smokers also demonstrated increased impulsive choice in the DDT relative to non-smokers (e.g. Reynolds, 2006; Fields et al., 2009; Pope et al., 2019; Carim-Todd et al., 2016). However, unlike some previous reports (e.g. Heyman and Gibb, 2006; Stillwell and Tunney, 2012), there was no significant difference between the light and heavy smoking groups, perhaps because ‘light smokers’ in the present study smoked daily and displayed higher levels of dependency. In contrast to impulsive choice, dimensions of behavioural disinhibition and reflection impulsivity did not differ across dependency levels. This is the first study to our knowledge that has explored reflection impulsivity across levels of nicotine dependency. However, the failure to find differences between non-smokers and light or heavier smokers on measures of inhibitory control has been commonly reported (e.g. Dinn et al., 2004; Reynolds et al., 2007; Field et al., 2009; Wilcockson et al., 2021), suggesting that heightened impulsive choice may be the most reliable indicator of smoking status. Whether heightened impulsive choice in smokers is due to nicotine exposure or a trait that may increase the risk of initiating smoking cannot be determined here, although evidence suggests that heightened delay discounting may be both a risk factor (Audrain-McGovern et al., 2009) and consequence (e.g. Kolokotroni et al., 2011; 2014) of smoking.

Critically, the present study revealed varying effects of nicotine deprivation across dimensions of impulsivity. In comparison to heavy satiated smokers, 12-hour deprived smokers displayed significantly poorer inhibitory control and heightened reflection impulsivity yet significantly *lower* levels of impulsive choice. This supports the heightened disinhibition previously observed following 3 to 72 hours of nicotine withdrawal across a range of inhibitory control tasks (Mendrek et al., 2006; Dawkins et al., 2007; Harrison et al., 2009; Charles-Walsh et al., 2014; Tsaur et al., 2015; Kalhan et al., 2022). The present study is the first to demonstrate that short-term withdrawal can also increase risky decision-making on the IST.

Importantly this impulsive decision-making was evident during both FW and DW trials, suggesting that nicotine deprivation may increase reflection impulsivity in both low and high-risk situations. The current findings extend previous research demonstrating heightened reflection impulsivity in other substance-using populations (e.g. Clark et al., 2006; 2009; Townshend et al., 2014; Stevens et al., 2015; Round et al., 2020), importantly however, for cigarette smokers, these impairments appear to be restricted to periods of withdrawal. Given the IST was designed to minimise demands on working memory and attention (Clark et al., 2006), it is unlikely that the risky decision-making was secondary to the detrimental effects nicotine deprivation can have on these elements of cognition (e.g. al'Absi et al., 2002; Mendrek et al., 2006; Myers et al., 2008). Deprived smokers did however take significantly longer to open boxes, potentially indicating lower levels of task-related motivation/arousal (Clark et al., 2006). However, they still displayed information sampling that varied according to the reward characteristics of the conditions, sampling less information during the DW than FW trials, suggesting they were still motivated to win points.

There are two potential explanations for why reflection impulsivity and disinhibition may increase during nicotine withdrawal. Firstly, acute/chronic nicotine may decrease these behaviours, masking underlying deficits in inhibitory control and risky decision-making. During withdrawal, in the absence of nicotine, these impairments become unmasked, accounting for the differences observed between satiated and deprived smokers. Indeed, research suggests acute nicotine can improve inhibition in both dependent smokers (Dawkins et al., 2007; Myers et al., 2008), and non-smokers with inhibitory control deficits (Levin et al., 1996; Potter and Newhouse, 2004; Potter et al., 2012). Whilst research has yet to explore the pharmacological effects of acute nicotine on reflection impulsivity, there is evidence from other risk-taking tasks (e.g. Balloon Analog Risk Task) that nicotine can reduce risky behaviour (Ryan et al., 2013b; Pilarski et al., 2014). Alternatively, nicotine withdrawal may itself actively induce impairments in inhibitory control and reflective decision-making. Nicotine withdrawal is associated with dramatic changes in neural mechanisms (e.g. reductions in dopamine, serotonin, and noradrenaline) known to be critically involved in the mediation of impulsive behaviours (e.g. Fung et al., 1996; Watkins et al., 2000; Jentsch et al., 2014). Neural changes in withdrawal may therefore give rise to maladaptive impulsive behaviour that is not otherwise present in dependent smokers.

Importantly, deprived smokers discounted delayed monetary rewards to a significantly lesser extent than satiated smokers. To date research has found that nicotine abstinence is associated with increased (Field et al., 2006; Yi and Landes, 2012; McCarthy et al., 2018) decreased (Yi et al., 2008), and no change in levels of delay discounting (Mitchell 2004; Roewer et al., 2015). Variations in baseline impulsivity, length of abstinence, and differences in the delay, magnitude, and commodity of task rewards, are likely to contribute to the discrepant results. One mechanism that may explain the decrease in impulsive choice during withdrawal is diminished reward sensitivity ('anhedonia'; see Hughes, et al., 2020 for review), which is associated with reduced motivation for financial rewards in withdrawing smokers (Powell et al., 2002; Dawkins et al., 2006). In the current study, reduced sensitivity to the immediate monetary rewards during deprivation may explain the greater selection of the delayed larger reward.

Deficits in self-control and attentional bias have long been theorised to operate simultaneously, working together to maintain drug-seeking and taking behaviour (Jentsch and Taylor, 1999; Dawe et al., 2004; Field and Cox, 2008; Coskunpinar and Cyders, 2013). The present study however revealed no evidence that attentional bias was related to impulsivity in cigarette smokers, instead, these mechanisms appeared to operate relatively independently from each other. The strongest evidence for this dissociation was in nicotine-deprived smokers, who displayed heightened levels of disinhibition and reflection impulsivity, yet *no* smoking-related attentional bias. The lack of association contrasts with findings suggesting that higher trait impulsivity, measured via the BAS sub-scales of the BIS/BAS, may be associated with quicker initial orientation and maintained attention towards smoking-related cues (Della Libera et al., 2019). The dimension of 'rash impulsivity' assessed by the BIS-11 in the current study is argued to be distinct from the type of 'reward sensitivity' measured by the BAS-Drive and BAS-Reward Responsiveness subscales (Dawe et al., 2004; Dawe and Loxton, 2004). It may be that an individual's response and motivation towards rewards are more predictive of levels of attentional bias in smokers than characteristics of risk-taking behaviour and lack of consideration of future consequences. Given the lack of significant association in the present study between smoking-related bias and impulsive choice on the DDT, these relationships may however only exist with trait, rather than behavioural, measures of reward sensitivity.

Stronger relationships between attentional bias and impulsivity may have been found if impulsivity was assessed specifically in the context of cigarettes. Supporting this, research in alcohol users revealed significantly stronger associations between alcohol Stroop bias and impulsive choice for alcohol than monetary rewards (Field et al., 2007), suggesting bias may be more strongly related to an inability to inhibit behaviour in response to drugs of dependence. More direct and continuous measures of attention, such as eye-tracking, may have also revealed stronger associations with impulsivity than VDP reaction times which only provide a snapshot of attentional bias. The present sample was also relatively small and consisted predominately of young adult smokers (university students and staff) of moderate dependency. Associations between impulsivity and bias may only emerge in larger, more diverse samples including smokers with a longer history of smoking and more severe dependence (Della Libra et al., 2019). It is also possible that smoking-related bias and its relationship with impulsivity would have been more pronounced after 24-48 hours of abstinence when withdrawal symptoms are at their peak (Hughes, 2007). The between-subject design may have additionally limited the interpretation of the impact of deprivation, although these groups did not differ on variables such as gender, age, dependence, and trait impulsivity, factors known to potentially influence impulsivity and attentional bias (e.g. Steinberg et al., 2008; Weafer and de Wit, 2014; Zhang, et al., 2020). Nevertheless, an important avenue for research is for smokers to perform tasks under both conditions of satiation and withdrawal following a longer period of abstinence.

Overall, these results make a significant contribution to our understanding of the role of impulsivity and attentional bias across the nicotine addiction cycle. Findings suggest that heightened non-planning and motor trait impulsivity may be vulnerability factors in the initiation of smoking, whilst enhanced motor impulsivity may be a critical risk factor in the transition to heavier, more dependent smoking. In both heavy and light smokers, attentional bias to smoking-related cues and heightened sensitivity to immediate gratification, appear to play a critical role in maintaining smoking during periods of nicotine satiation. In contrast, reduced levels of smoking-related bias and delay discounting observed during nicotine deprivation suggest that these mechanisms are unlikely to be involved in smoking relapse during the early stages of withdrawal. Instead, reduced inhibitory control and engagement in risky decision-making may play a more important role in predicting relapse at this stage. Critically, the lack of significant association between impulsivity and attentional bias suggests that each plays a unique and independent role in the development and maintenance of cigarette smoking. This has implications for clinical practice, supporting preliminary evidence that interventions aimed solely at either enhancing levels of self-control (e.g. Alcorn et al., 2017; Onie et al., 2019) or reducing attentional bias are unlikely to have a significant impact on the other, leaving individuals vulnerable to relapse. Whilst these findings question the strength of the association between impulsivity and attentional bias proposed by models of addiction, it is important that future research continues to explore their complex relationship to enhance our understanding of nicotine addiction.

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Figure Legends

Figure 1. Analysis across levels of nicotine dependency: Differences in levels of attentional bias towards smoking-related cues. Each bar represents mean reaction time ± SEM. * p <.05, as compared to neutral cue.

Figure 2a-b. Analysis across levels of nicotine deprivation: a) Differences in levels of attentional bias towards smoking-related cues b) Differences in levels of attentional bias towards smoking-related cues, image x smoking group interaction. Each bar represents mean reaction time ± SEM. * p <.05, as compared to neutral cue. † p <.05, †† p < 0.01, as compared to heavy satiated smokers.

Supplementary Materials

Supplementary Table 1. Levels of Dependency: comparison of behavioural impulsivity.

Supplementary Table 2. Levels of Dependency: relationship between impulsivity and attentional bias to smoking-related cues at 200ms exposure.

Supplementary Table 3. Levels of Dependency: relationship between impulsivity and attentional bias to smoking-related cues at 2000ms exposure

Supplementary Table 4. Levels of Deprivation: comparison of behavioural impulsivity.

Supplementary Table 5. Levels of Deprivation: relationship between impulsivity and attentional bias to smoking-related cues at 200ms exposure.

Supplementary Table 6. Levels of Deprivation: relationship between impulsivity and attentional bias to smoking-related cues at 2000ms exposure

Tables

Table 1. Participant sample demographics and smoking behaviour

	NON-SMOKERS	**LIGHT SATIATED SMOKERS**	**HEAVY SATIATED SMOKERS**	**HEAVY DEPRIVED SMOKERS**
N	26	25	23	30
Age years	27.27 (10.47)	21.60 (2.24)	23.26 (5.45)	23.57 (3.73)
Sex % Male	42.31	48.00	43.48	56.67
Cigarettes smoked per day	-	4.13 (2.29)	14.79 (2.89) ***	14.17 (6.11)
Years smoking tobacco	-	4.50 (2.81)	7.93 (5.79)	7.32 (3.90)
FTND Score	-	0.84 (1.11)	4.78 (1.91) ***	3.43 (2.36)
CO Level (parts per million)	-	4.76 (3.88)	16.00 (8.27) ***	5.33 (2.61) †††

Data presented as mean (SD). FTND = Fagerström test for nicotine dependence.
Analysis across levels of nicotine dependency: ****p* < .001, as compared to light satiated smokers;
Analysis across levels of nicotine deprivation: †††*p* < .001, as compared to heavy satiated smokers.

Table 2. Comparison of trait and behavioural impulsivity.

	NON-SMOKERS	LIGHT SATIATED SMOKERS	HEAVY SATIATED SMOKERS	HEAVY DEPRIVED SMOKERS
N	26	25	23	30
Trait Impulsivity				
BIS-11 Total	59.23 (8.84)	68.73 (10.43) **	75.57 (11.94) ***	72.53 (10.81)
BIS-11 Motor	22.15 (3.44)	25.89 (4.43) **	26.78 (4.38) **	26.33 (3.40)
BIS-11 Attention	15.88 (3.31)	17.68 (3.58)†	20.13 (3.73) ***	18.80 (4.23)
BIS-11 Non-planning	21.90 (4.62)	25.16 (4.53) *	28.66 (6.66) **	27.40 (4.96)
N	25#	23#	22#	29#
Delay Discounting				
Area Under the Curve	0.43 (0.22)	0.21 (0.22) ***	0.20 (0.16) ***	0.35 (0.24) ††
N	18§	20§	17§	28§
Stop Signal Task				
Stop Signal Reaction Time (ms)	261.48 (33.39)	239.28 (29.52)	237.24 (45.13)	269.14 (48.17) †
N	26	25	23	30
Information Sampling Task				
FW P. Correct	0.84 (0.12)	0.82 (0.10)	0.86 (0.12)	0.77 (0.10) ††
DW P. Correct	0.72 (0.09)	0.69 (0.09)	0.72 (0.08)	0.66 (0.08) ††

Data presented as mean (SD). Analysis across levels of nicotine dependency: *p < .05; **p < .01; ***p < .001, as compared to non-smokers; †p < .05, as compared to heavy satiated smokers. Analysis across levels of nicotine deprivation: †p < .05, ††p < .01, †††p < .001, as compared to heavy satiated smokers.

= Due to a technical error, 5 data sets for the delay discounting task were lost (Non-smokers n= 1; Light satiated smokers, n= 2; Heavy satiated smokers, n = 1; Heavy deprived smokers, n = 1).

§ = Due to the failure of successfully inhibiting their responses on 50% of the signal response trials or to respond to more than 10% of the no-signal trials, 21 data sets were excluded from the analysis of the SST (Non-smokers n= 8; Light satiated smokers, n= 5; Heavy satiated smokers, n = 6; Heavy deprived smokers, n = 2).

Table 3. Levels of Dependency: relationship between impulsivity and attentional bias to smoking-related cues

	Attentional Bias Towards Smoking Cues	
	BIAS 200ms	**BIAS 2000ms**
Heavy and Light Satiated Smokers (N=48)		
BIS Total	.044	.145
BIS Motor	.036	.097
BIS Attention	.075	.114
BIS Non-planning	.011	.139
AUC#	-.199	-.139
SSRT§	-.044	-.052
FW P. Correct	-.120	.-.193
DW P. Correct	-.036	-.122

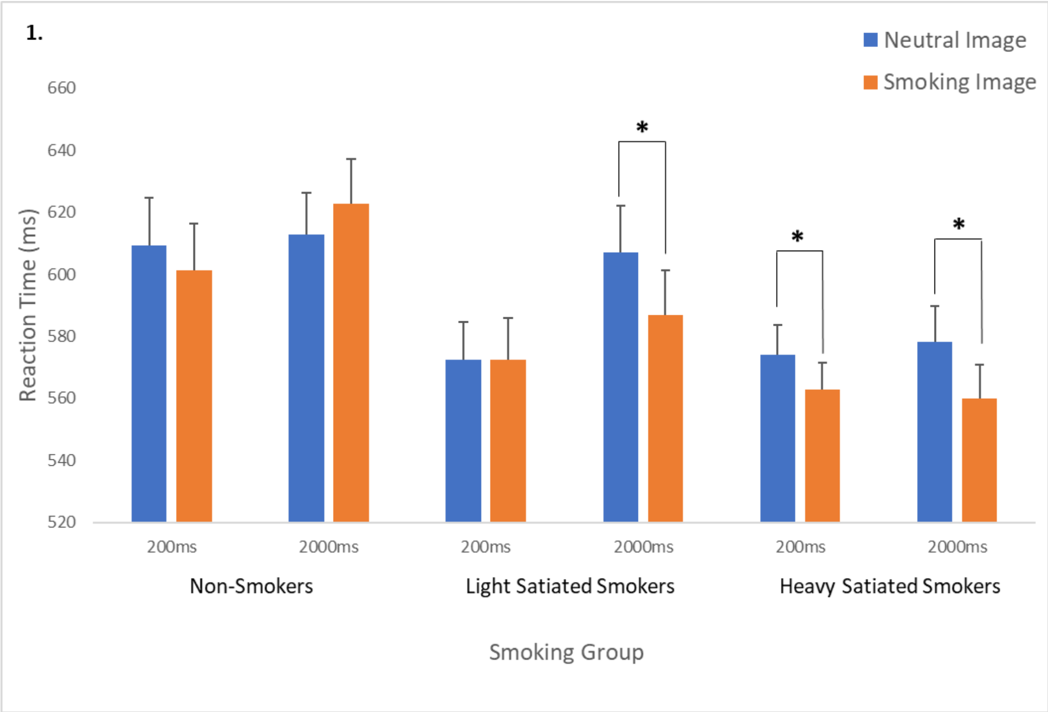
Data represent partial correlation *r* while controlling for level of dependency.
AUC = Area under the curve; SSRT = Stop signal reaction time; FW P.Correct = Fixed Win P(Correct); DW P.Correct = Decreasing Win P(Correct)
# = Due to a technical error, 3 data sets for the delay discounting task were lost (Light satiated smokers, n= 2; Heavy satiated smokers, n = 1).
§ = Due to the failure of successfully inhibiting their responses on 50% of the signal response trials or to respond to more than 10% of the no-signal trials, 11 data sets were excluded from the analysis of the SST (Light satiated smokers, n= 5; Heavy satiated smokers, n = 6).

Table 4. Levels of Deprivation: relationship between impulsivity and attentional bias to smoking-related cues

	Attentional Bias Towards Smoking Cues	
	BIAS 200ms	**BIAS 2000ms**
Heavy Deprived and Heavy Satiated Smokers (N=53)		
BIS Total	.003	.071
BIS Motor	-.063	.032
BIS Attention	.145	.147
BIS Non-planning	-.054	.016
AUC#	.085	-.201
SSRT§	-.142	-.217
FW P. Correct	.093	-.270
DW P. Correct	-.051	-.075

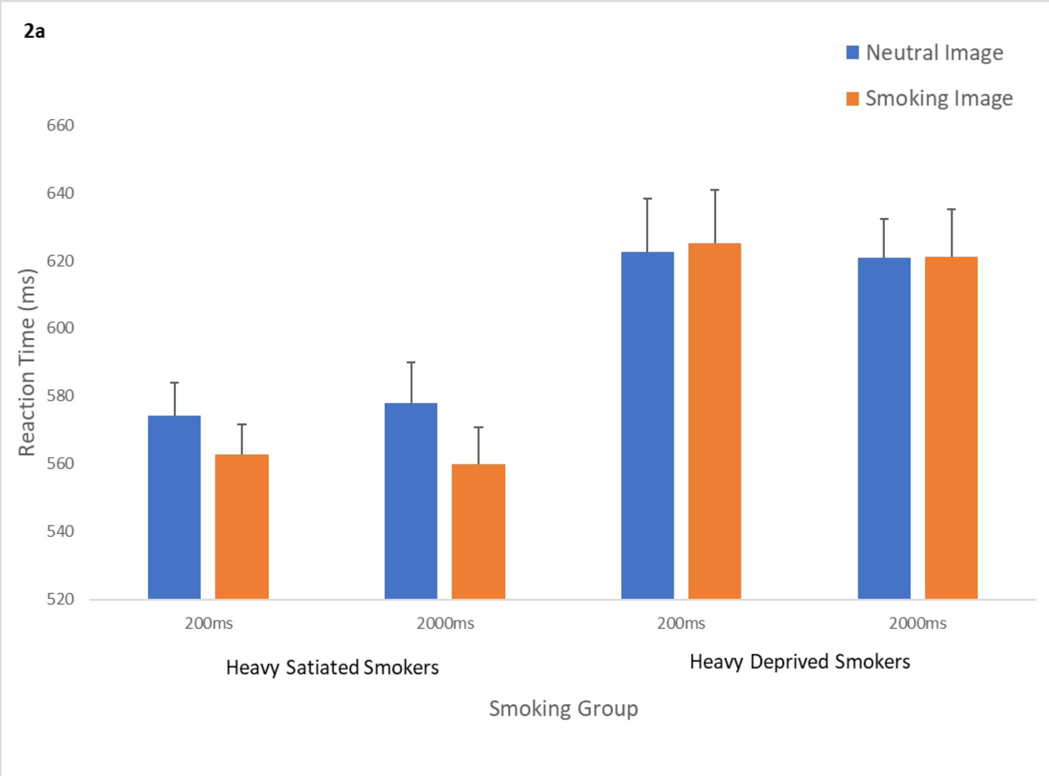
Data represent partial correlation *r* while controlling for level of deprivation.
AUC = Area under the curve; SSRT = Stop signal reaction time; FW P.Correct = Fixed Win P(Correct); DW P.Correct = Decreasing Win P(Correct)
# = Due to a technical error, 2 data sets for the delay discounting task were lost (Heavy satiated smokers, n = 1; Heavy deprived smokers, n = 1).
§ = Due to the failure of successfully inhibiting their responses on 50% of the signal response trials or to respond to more than 10% of the no-signal trials, 8 data sets were excluded from the analysis of the SST (Heavy satiated smokers, n = 6; Heavy deprived smokers, n = 2).

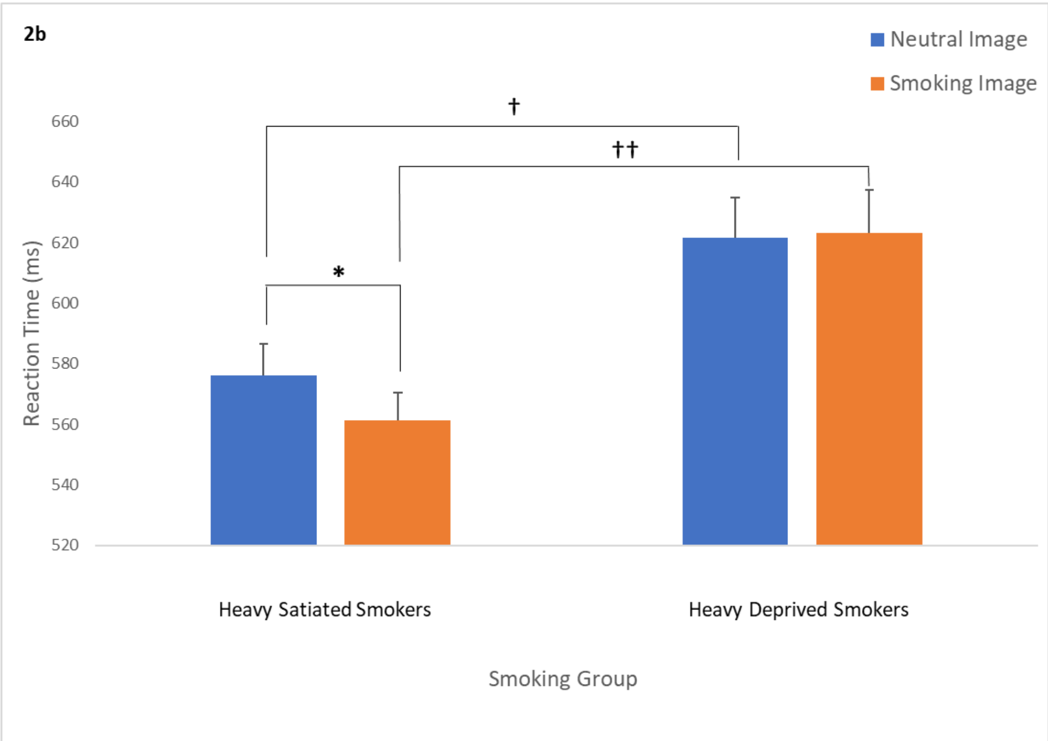
Figure



1.
Neutral Image
Smoking Image
660
640
620
600
580
560
540
520
Reaction Time (ms)
*
*
*
200ms
2000ms
200ms
2000ms
200ms
2000ms
Non-Smokers
Light Satiated Smokers
Heavy Satiated Smokers
Smoking Group

Figure


2a
Neutral Image
Smoking Image
Reaction Time (ms)
660
640
620
600
580
560
540
520
200ms
2000ms
200ms
2000ms
Heavy Satiated Smokers
Heavy Deprived Smokers
Smoking Group


2b
Neutral Image
Smoking Image
†
††
*
Reaction Time (ms)
660
640
620
600
580
560
540
520
Heavy Satiated Smokers
Heavy Deprived Smokers
Smoking Group