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Cognitive control over immediate reward in binge alcohol drinkers

Antoinette Poulton[a*] MEd, Caitlyn Mackenzie[a] BSc (Hons), Kaitlyn Harrington[a] BA (Hons), Sarah Borg[a] MPsych, and Robert Hester[a] PhD

[a]Melbourne School of Psychological Sciences, University of Melbourne, Parkville 3010, VIC, Australia

[*]Corresponding author:
Melbourne School of Psychological Sciences
Tel.: +61 3 8344 6377
Fax: +61 3 9347 6618
Email: antoinette.poulton@unimelb.edu.au

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Abstract

Background: Cognitive control deficits, as captured by inhibitory control measures, are indicative of increased impulsivity and are considered a marker for substance use disorder (SUD) vulnerability. While individuals with alcohol use disorder (AUD) typically exhibit inhibitory control dysfunction, evidence of impaired inhibitory control among harmful drinkers, who are at increased risk of developing an AUD, is mixed. This study examined the response inhibition of binge drinkers using a task that employed neutral, as well as both immediate and delayed reward contingencies, to determine whether reward induced heightened impulsivity in this population.

Methods: Binge alcohol users (n = 42) and controls (n = 42) were administered a Monetary Incentive Control Task that required participants to successfully inhibit a prepotent motor response to both neutral and immediately rewarding stimuli in order to secure a large delayed reward.

Results: Binge drinkers had significantly worse response inhibition than controls irrespective of trial condition and even after controlling for differences in weekly intake. Though both binge and control participants exhibited significantly worse inhibitory control in the presence of immediate reward, the control group showed a greater reduction in inhibition accuracy compared to the binge group in reward relative to neutral conditions. Both groups demonstrated significantly enhanced control when forewarned there was an increased chance response inhibition would be required. Control participants secured the delayed reward more often than binge participants.

Conclusions: Despite the variability in the literature, this study demonstrated consistent generalized impulse control deficits among binge drinking individuals that were unrelated to reward manipulations. These findings point to mechanisms that may confer vulnerability for transition from binge drinking to AUD.

Key words: Binge drinking; Cognitive control; Inhibitory control; Response inhibition; Reward

Introduction

Binge drinking refers to a pattern of alcohol consumption whereby recurrent episodes of heavy drinking are punctuated by periods of abstinence (Scaife and Duka, 2009). This type of drinking is especially prevalent among adolescents and young adults: 30-37% of young people in the United States and 21-56% of those in Europe regularly binge drink (Hibell et al., 2012; Johnston et al., 2013). The specific pattern of alcohol misuse that characterizes bingers – that is, regular acute intoxications and repeated withdrawals – appears to introduce specific cognitive deficits over and above those associated with total alcohol consumed (Petit et al., 2014). Critically, early onset of heavy drinking has been identified as a significant predictor of AUD, and binge-drinking trajectories throughout college years have been found to predict alcohol abuse and dependence ten years later (Dawson et al., 2008; Jennison, 2004). At the same time, given the worldwide prevalence of AUD is 2.3%, the vast majority of young people who binge drink do not, in fact, develop this disorder (WHO, 2014). Nevertheless, the binge drinking population provides an opportunity to investigate if the cognitive control deficits characterizing AUD individuals are also apparent in

binge (but not non-binge) drinkers. In this way, mechanisms influencing the transition from binge drinking to AUD might be identified.

Current theories related to SUDs, including AUD, implicate heightened impulsivity as a key factor underpinning the loss of control evident in these disorders (Goldstein and Volkow, 2011). Behaviorally, impulsivity is recognized as a multi-faceted concept incorporating the inability to regulate instincts and desires, and the tendency to act without planning or considering consequences (Fernie et al., 2010; MacKillop et al., 2011). Increased impulsivity, and hence vulnerability for SUD, is postulated to arise from an imbalance between bottom-up reward-sensitive processes, which are subserved by striatal and limbic areas, and top-down cognitive control mechanisms, which are mediated by the prefrontal cortex (Stevens et al., 2014; Verdejo-García and Bechara, 2009). Impaired inhibitory control, which refers to a failure to successfully inhibit a dominant behavioral response, captures deficits in cognitive control and is thus considered one independent marker of impulsivity (Field et al., 2007; Murphy and Garavan, 2011). Typically, Go/No-Go and Stop-Signal tasks are employed in the investigation of inhibitory control (Fernie et al. 2010). Such tasks require participants to respond rapidly to specific frequently appearing stimuli, but to inhibit responses to others that are presented less often (Murphy and Garavan, 2011). Elevated commission errors, decreased successful inhibitions, and increased reaction times on these tasks all signal poor inhibitory control, and are thereby indicative of heightened impulsivity (Ahmadi et al., 2013; Lawrence et al., 2009).

Individuals with SUDs commonly display signs of impaired inhibitory control (Bickel et al., 2012; Smith et al., 2014; Verdejo-García et al., 2008). With regard to AUD, research has demonstrated that dependents, those undergoing detoxification, and newly abstinent individuals have significantly longer Stop-Signal reaction times (SSRTs) and substantially elevated No-Go commission errors, as compared to controls (Goudriaan et al., 2005, 2006; Lawrence et al., 2009; Noël et al., 2007). By contrast, investigations into the inhibitory control of non-dependent binge or heavy drinkers have generally yielded less consistent results. While Smith and Mattick (2013) found female heavy drinkers had significantly longer SSRTs than light drinkers, other studies utilizing inhibitory control measures have been unable to distinguish the performance of heavy or binge drinkers from that of healthy controls (Henges and Marczinski, 2012; Moreno et al., 2012). Similarly, although Henges and Marczinski (2012) demonstrated Go/No-Go performance predicted the number of

drinks consumed by young social drinkers on one occasion, Fernie and colleagues (2010) found no evidence to suggest either Go/No-Go or Stop-Signal tasks predicted alcohol misuse in healthy participants. In cases where inhibitory control measures have not successfully discriminated between heavy or binge drinking individuals and controls, significant brain function anomalies have nonetheless been identified in at-risk drinkers during response inhibition: specifically, binge drinking has been associated with altered event related potentials in frontal regions, and reduced brain activation in areas associated with impulsivity (Ahmadi et al., 2013; López-Caneda et al., 2012; Whelan et al., 2014; Yan and Li, 2009). Consequently, while inhibitory control impairments among heavy or binge drinkers might not always be apparent behaviorally, they appear more evident at the brain function level.

As increased impulsivity is speculated to arise from irregularities in both top-down cognitive control and bottom-up reward sensitive mechanisms, it is possible inhibitory control tasks incorporating reward might better detect behavioral differences between SUD individuals, or those at risk of the disorder, and healthy controls. The inclusion of a reward condition has been found to significantly enhance the inhibitory control of SUD individuals, but not healthy controls, and this has led to the assertion reward sensitivity modulates inhibitory control among those with SUDs (Chung et al., 2011). With regard to alcohol misuse, passive-avoidance Go/No-Go measures, which require participants to learn No-Go stimuli via rewarding and punishing feedback, have been used to demonstrate an association between heavy alcohol use or binge drinking and commission errors (Castellanos-Ryan et al., 2011; Colder and O'Connor, 2002). Such measures, however, incorporate an element of learning, making it difficult to disambiguate the extent to which they are sensitive to failures of learning or inhibitory control (or the combination therein). Employing a Go/No-Go task with neutral, reward, and punishment contingencies, Rossiter and colleagues (Rossiter et al., 2012) found no significant difference between harmful and non-harmful drinkers under neutral conditions; however, reward significantly improved the inhibitory control accuracy of the harmful drinkers, and thereby differentiated harmful from non-harmful users. Thus, inhibitory control tasks incorporating reward not only quantify behavioral deficits in inhibitory control among sub-clinical samples, but also capture the reward sensitivity of these individuals.

Harmful sub-clinical drinkers include individuals who binge drink, as well as those who are characterized by an elevated total alcohol intake independent of rate

and frequency of consumption. Previous work has not typically examined the cognitive performance of bingers using inhibitory control measures incorporating reward. Given the findings of greater sensitivity of such measures in the healthy population, performance within the binge-drinking cohort may be more sensitive to the individual differences that appear critical to the risk of transitioning to AUD. As such, this study investigated differences in inhibitory control between binge drinkers and controls using a novel measure that employs neutral, as well as both immediate and delayed reward contingencies. This measure attempts to emulate the real-world scenario encountered by bingers whereby a failure to inhibit a prepotent response for a reward-related stimulus (e.g., alcohol) produces an immediate certain reward (e.g., reduced craving), with no direct immediate punishment. By contrast, successfully inhibiting the impulse for alcohol tends to result in the greater delayed rewards associated with abstinence (e.g., improved health). In the current task, inhibition failures generate small, secure, immediate rewards, while successful inhibitions contribute to the likelihood of obtaining a larger, delayed reward. Additionally, the task forewarns participants of the probability response inhibition will be required.

It was hypothesized binge/control group differences would be more evident under rewarding, but not neutral conditions, and when the probability of response inhibition over reward was most likely. Specifically, it was predicted that relative to the neutral condition, the immediate reward condition would reduce inhibition accuracy on a Monetary Incentive Control Task (MICT) to a greater extent in the binge group than the control group. We envisaged the binge group would favour a strategy that maximized their chance of obtaining immediate secure reward. As failure to inhibit resulted in such rewards, we therefore expected the binge group to demonstrate reduced inhibitory control. By contrast, we assumed the control group would adopt a strategy that enhanced their chances of securing the delayed reward, namely increased inhibitory control across both neutral and reward conditions. It was further predicted that inhibition accuracy on the MICT would be enhanced when participants were alerted there was a 40%, compared to 20%, chance of response inhibition. We anticipated this effect would be more evident in the control group.

Materials and Methods

Participants

Ninety-one participants (46 female, mean age 22.90) were recruited from the University of Melbourne and via experimenter networks. Suitability for the study was

evaluated via a screening questionnaire, the Fagerström Test for Nicotine Dependence (Heatherton et al., 1991), and the Drug Abuse Screening Test (Skinner, 1982). Exclusion criteria included history of neurological or psychiatric illness, current use of psychoactive medications, nicotine dependence, AUD, and/or abuse of drugs other than alcohol. Participants were fluent in English. The University of Melbourne's Human Ethics Committee approved the study in accordance with the standards for ethical research of the National Health and Medical Research Council. All participants provided informed consent. They were reimbursed for their time (AU$10 per hour), and received additional monetary rewards commensurate with task performance.

In accordance with criteria detailed by López-Caneda and colleagues (López-Caneda et al., 2012, 2013), participants were classified as binge drinkers or controls on the basis of their responses to the Alcohol Use Disorders Identification Test (AUDIT; Saunders et al., 1993), which asks participants to consider their alcohol consumption over the previous twelve months, and other questions regarding alcohol use over the preceding six months. Participants were designated as binge drinkers (n = 42) if (i) they consumed six or more standard alcoholic drinks (standard drinks contain 10g of alcohol in Australia) per drinking occasion two to three times per week, or (ii) if they consumed six or more standard drinks per drinking occasion two to four times per month and drank in excess of two standard drinks per hour. Controls consumed alcohol below the levels necessary for these criteria (n = 42). Regular heavy drinkers (n = 7) were excluded from the analysis. These individuals indicated they drank alcohol four or more times per week and that when drinking they consumed, on average, more than four (4.86) standard drinks per session.

Monetary Incentive Control Task (MICT)

Inhibitory control was evaluated using the MICT (Fig. 1). Programmed using E-Prime software (version 2.0, Psychology Software Tools) and running on a laptop PC, MICT stimuli presentation and recording of responses were digitally controlled. The task comprised one practice block followed by three blocks of 72 trials. Cues indicated trials would be one of four randomly assigned conditions: Neutral20, Reward20, Neutral40, and Reward40. Cue color – white or red – signified the probability of an inhibition trial – 20% or 40% chance respectively. Within each block, 25% of all trials were inhibition trials. Cue shape denoted the reward contingency of each trial. A horizontal line (-) designated neutral conditions (50% of

trials), in which participants would not receive any immediate reward regardless of performance, while an apex symbol (^) indicated reward conditions (50% of trials), where participants could secure an immediate and certain AU$0.20 reward, depending on their response. Thus, participants were able to use cues to anticipate trial type.

Stimuli took the form of letter X or O. During go trials, participants were required to press the corresponding letter on the keyboard within 400ms, and received immediate feedback regarding accuracy and monetary gain. The 400ms response window was designed to encourage fast responding to go trials and was taken directly from the widely used and validated Monetary Incentive Delay task (Knutson, Fong, Adams, Varner, & Hommer, 2001) from which the MICT is an adaption. The response time limit made it more difficult to inhibit the prepotent response when required and discouraged participants from adopting a strategy of slowing their go responses in order to more easily withhold their response on inhibitory trials. During inhibition trials, a square appeared around the X or O after 150ms, thereby indicating participants were to withhold their response. In both neutral and reward conditions, successful inhibition of response did not result in an immediate certain reward, but counted toward a larger delayed reward at task end. Participants were instructed that successful inhibition of 60% or more of all inhibition trials would result in a large delayed reward (AU$20.00) upon task completion. Failed inhibition in neutral conditions resulted in no (immediate or delayed) reward. By contrast, inhibition failures during reward conditions yielded participants an immediate and certain AU$0.20 reward (but did not count toward the larger delayed reward). Thus, failure to inhibit a response for a reward-related stimulus produced a small immediate certain reward – much like the failure to inhibit alcohol consumption results in immediate reward (e.g., reduced craving) – whereas successfully inhibiting a response for a reward-related stimulus increased the chance of securing the larger delayed reward – much as successfully inhibiting alcohol consumption contributes to improved health and other less immediate outcomes. In short, participants needed to balance their desire for immediate versus delayed reward throughout the task. Those swayed by immediate certain reward were likely to adopt a strategy designed to ensure successful responding to immediately rewarding (as opposed to neutral) stimuli. Although profitable in the short-term, this may have diminished their ability to inhibit their response when required and thus impacted their chances of acquiring the larger

delayed reward. Participants less influenced by immediate reward were likely to enact a strategy that maximized their capacity for inhibiting a response when required. Although this impacted money acquired via short-term immediate reward, it increased their chance of securing the larger delayed reward at the end of the experiment.

Several mechanisms were employed to ensure participants thoroughly understood the task prior to commencement. In the first instance, the researcher read through the on-screen instructions with each participant and gave them the opportunity to ask questions or seek clarification. The researcher provided a verbal précis of what each cue represented, the type of feedback participants could expect after each trial, the immediate/delayed reward trade-off, and the need to respond as fast as possible on all trials. Participants then undertook a practice block. During this block, cue symbols – white/red and -/^ – were accompanied by text – "20%"/"40%" and "neutral"/"reward" – reminding participants of the significance of cues. Additionally, the researcher sat beside the participant during this block and issued further clarification as required, reiterated the significance of cues as necessary, and reminded participants of the need to respond as fast as possible on all trials regardless of their go or potential inhibitory status. If participants appeared to be adopting a strategy of non-responding to go trials at any point during the practice block, they were told this was contrary to task requirements and that they needed to attempt to respond to all trials. Thus, prior to undertaking experimental blocks of trials, researchers ensured participants understood the task and were responding to cues/trials as directed by the task.

At the conclusion of each block, participants received feedback regarding sub-400ms threshold go trial performance and total money earned from immediate rewards in that block, but not inhibition trial accuracy. Running totals across blocks of trials were not provided so participants were unable to determine whether their behavioral responses were likely to secure the delayed reward. Upon completion of the task, participants were given feedback regarding total money earned from immediate certain reward, plus their inhibition accuracy in each of the reward and neutral conditions across all blocks. The proportion of successful inhibitions for each of the four conditions provided a measure of inhibitory control accuracy. Relative to neutral inhibitory trials, reward trials provided an indication of the extent to which the prospect of immediate certain reward reduced inhibitory control.

Statistical Design and Analysis

A one-way analysis of variance (ANOVA) and chi-square test were conducted to assess if binge and control groups were matched demographically. Differences in performance across the four conditions on the MICT were analyzed using a mixed repeated measures ANOVA, with inhibition probability (20%, 40%) and reward type (neutral, reward) as the within subjects factors, and group (binge, control) as the between subjects factor. Age was identified as differentiating groups and was entered into the analysis as a covariate. Effect sizes were computed using partial eta squared values (η^2_p) and were interpreted according to Cohen's guidelines: .01 = small, .06 = moderate, and .14 = large effect (Cohen, 1988).

Results

Descriptive statistics

Descriptive statistics are displayed in Table 1. A one-way ANOVA revealed binge and control groups did not differ significantly on NART IQ, $F(1, 82) = 0.04$, $p = .847$, drug use, $F(1,82) = 3.09$, $p = .083$, nicotine dependence, $F(1, 82) = 0.68$, $p = .413$, or gender, $\chi^2(1, N = 84) = 3.08$, $p = .079$, but did differ on age, $F(1,82) = 10.67$, $p = .002$, total AUDIT score, $F(1,82) = 78.93$, $p < .001$, standard drinks consumed per week, $F(1,82) = 31.29$, $p < .001$, occasions consuming six or more drinks, $F(1,82) = 218.37$, $p < .001$, hourly rate of consumption, $F(1,82) = 66.80$, $p < .001$, and percentage drunkenness, $F(1,82) = 47.57$, $p < .001$. The binge group had higher AUDIT scores, drank more standard drinks per week, consumed six or more drinks on each drinking occasion more regularly, drank faster, and became intoxicated more frequently than the control group.

MICT performance

Inhibition mean accuracy, represented as the percentage of successful inhibitions for each condition, for binge and control groups is displayed in Table 2. The ANOVA determined there was a significant main effect of group, $F(1, 81) = 8.91$, $p = .004$, $\eta^2_p = .10$, inhibition probability, $F(1, 81) = 7.18$, $p = .009$, $\eta^2_p = .08$, reward type, $F(1, 81) = 8.75$, $p = .004$, $\eta^2_p = .10$, but not age, $F(1, 81) = 0.41$, $p = .523$, $\eta^2_p = .01$, on inhibition accuracy. Inhibition accuracy was higher for the control group, as well as in the 40% probability and neutral conditions. There was a significant interaction between group and reward type, $F(1, 81) = 8.25$, $p = .005$, $\eta^2_p = .09$, with the control group showing a greater reduction in inhibition accuracy compared to the binge group in reward relative to neutral conditions. There was no significant interaction between group and inhibition probability, $F(1, 81) = 0.01$, $p =$

.909, η^2_p < .01, inhibition probability and reward type, $F(1, 81) = 1.34$, $p = .250$, η^2_p = .02, or between group, reward type and probability, $F(1, 81) = 1.79$, $p = .185$, η^2_p = .02. Age did not interact with any factors. The analysis was repeated using standard drinks consumed per week as an additional covariate. None of the significant main or interaction effects from the preceding analysis changed. There was no significant main effect of standard drinks consumed per week, $F(1, 80) = 1.54$, $p = .219$, η^2_p = .02. A chi-square test indicated that more individuals in the control group (n = 11) than the binge group (n = 5) secured the delayed reward, though this was not a significant association, $\chi^2(1, N = 84) = 2.78$, $p = .095$, OR = 0.38, 95% CI [0.12, 1.21].

Go trial mean threshold performance, represented as the proportion of successful sub-400ms responses in each condition, for binge and control groups is displayed in Table 2. The ANOVA indicated there was no significant main effect of group, $F(1, 81) = 0.26$, $p = .609$, η^2_p < .01, or age, $F(1, 81) = 0.04$, $p = .843$, η^2_p < .001, on mean go threshold performance. There was a significant main effect of inhibition probability, $F(1, 81) = 5.22$, $p = .025$, η^2_p = .06, and reward type, $F(1, 81)$ = 20.45, $p < .001$, η^2_p = .20, on mean go threshold performance. Go threshold performance was higher in the 20% probability and reward conditions. There was a significant interaction between group and reward type, $F(1, 81) = 6.72$, $p = .011$, η^2_p = .08, with the control group showing a greater increase in go accuracy compared to the binge group in reward relative to neutral conditions. There was no significant interaction between group and inhibition probability, $F(1, 81) = 0.17$, $p = .683$, η^2_p < .01, inhibition probability and reward type, $F(1, 81) = 0.17$, $p = .683$, η^2_p < .01, or group, inhibition probability and reward type, $F(1, 81) = 0.66$, $p = .419$, η^2_p = .01.

Mean go trial threshold reaction times for binge and control groups across conditions are displayed in Table 2. The ANOVA determined there was a significant main effect of inhibition probability, $F(1, 76) = 7.12$, $p = .009$, η^2_p = .09, with go threshold reaction times slower in the 40% condition. There was no significant main effect of group, $F(1, 76) = 3.57$, $p = .063$, η^2_p = .05, reward, $F(1, 76) = 0.71$, $p = .404$, η^2_p = .01, or age, $F(1, 76) = 1.98$, $p = .164$, η^2_p = .03, on go trial threshold reaction times. There was also no significant interaction between group and inhibition probability, $F(1, 76) = 2.30$, $p = .133$, η^2_p = .03, group and reward, $F(1, 76) = 0.77$, p = .383, η^2_p = .01, inhibition probability and reward, $F(1, 76) = 0.08$, $p = .781$, η^2_p < .01, or inhibition probability, reward and group, $F(1, 76) = 3.23$, $p = .076$, η^2_p = .04.

Mean failed inhibition trial reaction times for binge and control groups across conditions are also displayed in Table 2. The ANOVA determined there was no significant main effect of group $F(1, 73) = 1.60$, $p = .211$, $\eta^2_p = .02$, reward, $F(1, 73) < 0.01$, $p = .984$, $\eta^2_p < .01$, inhibition probability, $F(1, 73) < 0.01$, $p = .969$, $\eta^2_p < .01$, or age, $F(1, 73) = 0.47$, $p = .494$, $\eta^2_p = .01$, on failed inhibition trial reaction times. There was a significant interaction between inhibition probability and group, $F(1, 73) = 9.46$, $p = .003$, $\eta^2_p = .12$, with controls exhibiting slower failed inhibition reaction times than binge drinkers in the 40% relative to 20% inhibition probability condition. There was no significant interaction between group and reward, $F(1, 73) = 0.06$, $p = .808$, $\eta^2_p < .01$, probability and reward, $F(1, 73) = 0.87$, $p = .353$, $\eta^2_p = .01$, or group, reward and probability, $F(1, 73) = 0.25$, $p = .617$, $\eta^2_p < .01$.

Discussion

This study examined differences in response inhibition among binge drinkers and controls utilizing an inhibitory control task that incorporated reward. The task required participants to consistently inhibit responses to reward-related stimuli – despite the fact that failure to do so generated small, certain, immediate rewards – in order to increase their chances of securing a larger, delayed reward. It was hypothesized group differences would be apparent under rewarding, but not neutral conditions, and when the probability of response inhibition over reward was most likely. The results indicate that, compared to controls, bingers had a significantly reduced ability to withhold their response to inhibition stimuli regardless of the reward or response inhibition probability condition. Compared to the neutral condition, both binge drinkers and controls performed significantly worse in the reward condition. Contrary to expectations, control participants, not binge drinkers, demonstrated a greater reduction in inhibition accuracy in reward relative to neutral conditions. Compared to the 20% condition, bingers and controls both performed significantly better when alerted there was a 40% chance they would be required to inhibit a response. Controlling for weekly intake did not alter these findings.

Previous investigations into the response inhibition of binge and heavy drinking individuals have generated mixed results. Although SSRTs have been found to distinguish heavy from light female drinkers (Smith and Mattick, 2013) and Go/No-Go performance has predicted the number of alcoholic beverages consumed by a sample of young 'social' drinkers (Henges and Marczinski, 2012), inhibitory

control tasks have often failed to differentiate the performance of heavy or binge drinkers from that of controls (Fernie et al., 2010; Moreno et al., 2012). This has lead to the hypothesis that in the absence of immediate reward or punishment, such tasks might be insensitive to revealing distinctions between harmful and non-harmful drinkers (Fernie et al., 2010). Such a proposition is consistent with evidence demonstrating heightened impulsive decision-making for reward, as measured by delay discounting procedures, among non-dependent harmful drinkers (Field et al., 2007; MacKillop et al., 2011). To date, many studies utilizing inhibitory control tasks incorporating reward and punishment have been confounded by the inclusion of a learning element (Castellanos-Ryan et al., 2011; Colder and O'Connor, 2002). Previous work has not typically considered the ability of binge or heavy drinkers to inhibit a response for immediately rewarding stimuli in order to secure a greater delayed reward, yet this is arguably more analogous to the real-world scenario encountered by this population. That is, in reality individuals must inhibit a response for an immediately rewarding stimulus (alcohol) in order to increase their chance of securing a larger delayed reward (healthier outcomes). While the present study employed a task that attempted to model this real-world situation, controls rather than binge drinkers demonstrated the greater reduction in inhibitory control in the presence of immediate reward. Nevertheless, the ability of binge drinkers to exercise inhibitory control – either in neutral or immediately rewarding conditions – was vastly inferior to control participants, even after controlling for weekly alcohol intake. Indeed, the mean inhibitory control accuracy of bingers in the neutral condition was less than that of controls in the reward condition. Thus, the inhibitory control of bingers in the neutral condition was already critically low and got worse still in the presence of immediate reward. Furthermore, these inhibitory control deficits account for why binge drinkers secured the delayed reward, which required at least 60% inhibition accuracy in both neural and immediate reward conditions, at less than half the rate of controls.

No binge/control group differences were evident upon examination of go threshold accuracy data. Indeed, participants responded to reward and inhibition probability manipulations largely as expected in these trials: the immediate reward condition induced higher accuracy as compared to the neutral condition, whereas the 40% condition reduced accuracy relative to the 20% condition. While increased go threshold accuracy in the presence of immediate reward intimates possible faster

responding in this condition, neutral and reward go threshold reactions times were not dissimilar. Incentive for immediate monetary reward, not enhanced reaction time, thus drove increased go threshold accuracy in the reward condition. By contrast, decreased accuracy on go threshold trials in the 40% condition was probably underpinned by the significantly slower reaction times participants secured in this condition. Importantly, there were no reaction time binge/control group differences on go trials. Although binge participants trended toward having reduced go trial threshold reaction times across conditions – suggesting their incentive for monetary reward influenced the speed with which they responded to all stimuli – in fact, these differences were not significant. As such, this cannot account for the reduced inhibition trial accuracy of binge drinkers across conditions.

Given the cross sectional nature of this analysis, it is difficult to determine whether the reduced inhibitory control of our binge sample represents a cause or consequence of their drinking behaviour. A number of studies suggest behavioural inhibitory control deficits might constitute a pre-existing risk factor for alcohol-related problems. A longitudinal study of 498 children, for example, has shown response inhibition in early adolescence predicted illicit drug use and the onset of problematic alcohol consumption, independent of other risk factors (Nigg et al., 2006). Likewise, researchers have determined that individual differences in inhibitory control among young adolescents predicted alcohol use and misuse six months later (Fernie et al., 2013). Although few behavioural studies consider the relationship between chronic bingeing and the progressive deterioration of inhibitory control, imaging studies provide some insight into the consequences of binge drinking. For instance, baseline differences in event-related potentials – elicited during a response inhibition task – between persistent binge and control groups were found to be more pronounced at two-year follow-up (López-Caneda et al., 2013). Wetherill and colleagues (2013) have demonstrated that adolescents who transitioned to heavy drinking had different neural activation patterns when undertaking a go/no-go task, as compared to non-drinking youngsters, both prior to and following the initiation of heavy drinking. Relative to non-drinkers, future heavy drinkers were characterized by reduced activation prior to transition but increased activation after transition (Wetherill et al., 2013). Thus, pre-existing inhibitory control impairments appear to signal vulnerability for the development of alcohol-related problems. At the same

time, persistent alcohol misuse impacts the neural mechanisms underpinning response inhibition and presumably thereby exacerbates the deficit.

The failure to show a specific deficit for binge drinkers in controlling responses to reward may, in part, be due to the sensitivity of the MICT. The inhibition trial accuracy of binger drinkers was poorer than expected, irrespective of condition, with performance in the 20% reward condition demonstrating floor effects. Indeed, the median (0.15) in this condition was less than the mean (0.22) and the boxplot indicated 25% of all accuracy values fell below 0.08 while 75% of values fell below 0.23, thereby suggesting substantial positive skew. Additionally, although control participants secured the delayed reward more frequently than bingers, this was not a significant effect, suggesting it might not have been a sufficiently lucrative reward. In order to encourage task compliance in both the neutral and immediate reward contingencies, the delayed reward was linked to performance in both conditions. That is, participants needed to successfully inhibit their response to all Stop stimuli at least 60% of the time in order to secure the delayed reward. As such, the neutral task presented an incentive for cautious behavior that may have masked some of the interaction between binge group and reward condition.

One consideration with the current study is whether our binge sample was representative of the binge drinking population. Non-dependent at-risk alcohol consumption is variously described in the literature as heavy, problem, or binge. Heavy and problem drinking may, however, refer to total intake rather than any specific binge pattern of consumption. As binge drinking has been found to result in cognitive effects over and above those associated with total consumption, it is important to take intake pattern into consideration (Petit et al., 2014). Indeed, the number of alcohol doses per drinking occasion, as opposed to total consumption levels, has been related to the cognitive and neural dysfunction identified in binge drinkers (Maurage et al., 2012; Petit et al., 2014). At the same time, it has been suggested operational definitions of binge drinking ought to incorporate quantity consumed over a specific timeframe plus the time period of episodes (Courtney and Polich, 2009). To this end, this study considered drinking episodes per week/month, alcohol doses per drinking occasion, and rate of consumption over the previous six to twelve months. Furthermore, heavy regular drinkers were excluded from the analysis in an effort to prevent behavioral deficits related to high total intake confounding results. The AUDIT scores of the current binge sample (13.21) were in keeping with

those of participants classified as binge in other studies (e.g., 10.4-11.2 in Fillmore and Jude, 2011). Similarly, binge drinkers in this study corresponded to those described in studies by Lopez-Caneda and colleagues (López-Caneda et al., 2012, 2013) with regard to AUDIT scores (13.21 in this study versus 10.7-12.1), occasions consuming six or more drinks (2.43 versus 2.8-2.9), weekly intake (11.52 versus 13.2-14.3) and percentage drunkenness (53.44 versus 52.5-55.4). Thus, the current binge sample appears to be representative of the binge drinking population sampled in other studies.

In sum, cognitive control impairments, as captured by inhibitory control tasks, are indicative of heightened impulsivity. Although increased impulsivity has been identified as a key factor underpinning the loss of control apparent in AUD, evidence of cognitive control impairments in non-dependent binge or heavy drinkers has been mixed. This study utilised a novel inhibitory control task that incorporated reward to explore the cognitive control of binge drinkers. We found that relative to control participants, bingers were characterised by significantly lower response inhibition performance, regardless of the reward or response inhibition probability condition. In the reward condition, where participants were required to consistently inhibit a response for reward-related stimuli – even though failure to do so generated small, certain, immediate rewards – in order to increase their chances of securing a larger delayed reward, both groups demonstrated reduced inhibitory control as compared to the neutral condition. At the same time, reward improved go trial threshold accuracy in both groups. It is possible aspects of the task contributed to the unexpected finding with regard to the interaction between binge group and reward across inhibitory trials. In particular, the balance between the immediate but secure small reward and the delayed but uncertain larger reward was perhaps not sufficiently refined. The current data nonetheless provide encouragement that novel response inhibition tasks can furnish unique indicators of control problems in binge drinkers that might be used for identifying those at risk of transitioning to AUD.

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Fig. 1. Examples of Monetary Incentive Control Task (MICT) display sequences. A fixation point of 1000ms followed by a cue of 2000ms preceded each trial. (a) Go trial in the Neutral40 condition. The red horizontal cue indicated a 40% probability of response inhibition plus no immediate monetary reward (i.e., neutral) for a successful response. If the participant responded to the go stimulus within 400ms, the feedback screen signaled a *hit*; otherwise, a *miss* was indicated. As the trial was neutral, there was no monetary reward for a *hit* or *miss*. (b) Go trial in the Reward20 condition. The white apex cue indicated a 20% probability of response inhibition plus immediate monetary reward for a successful response. If the participant responded to the go stimulus within 400ms, the feedback screen signaled a *hit* and the participant was rewarded AUS$0.20; otherwise, a *miss* was indicated and there was no monetary reward. (c) Inhibition trial in the Neutral20 condition. The white horizontal cue indicated a 20% probability of response inhibition plus no immediate monetary reward (i.e., neutral). If the participant successfully inhibited their response to the inhibition

stimulus, the feedback screen signaled *correct*; otherwise, *wrong* was indicated. As the trial was neutral, there was no monetary reward for *correct* or *wrong*. (d) Inhibition trial in the Reward40 condition. The red apex cue indicated a 40% probability of response inhibition plus immediate monetary reward. If the participant successfully inhibited their response to the inhibition stimulus, the feedback screen signaled *correct*; however, there was no immediate reward as this successful response counted toward securing a larger delayed reward at task end. If the participant failed to inhibit their response, *wrong* was indicated and there was an immediate monetary reward. In this case, the participant secured an immediate reward, but their response did not increase their chance of receiving the larger delayed reward at the completion of the experiment.

Table 1. Means, standard deviations, and confidence intervals of demographic and alcohol use data for the analysis sample (N = 84), including binge (n = 42) and control (n = 42) groups.

	Total		Binge		Control	
	M (*SD*)	95% CI	*M* (*SD*)	95% CI	*M* (*SD*)	95% CI
Age	22.77 (5.26)	[21.63, 23.91]	21.00 (3.31)	[19.97, 22.03]	24.55 (6.21)	[22.61, 26.48]
Age range	18-43		18-35		18-43	
Gender (F:M)	46:38		19:23		27:15	
NART IQ	111.48 (5.24)	[110.34, 112.61]	111.36 (4.85)	[109.85, 112.88]	111.59 (5.66)	[109.82, 113.35]
DAST	0.99 (1.57)	[0.65, 1.33]	1.29 (1.57)	[0.80, 1.77]	0.69 (1.54)	[0.21, 1.17]
FTND	0.05 (0.26)	[-0.01, 0.11]	0.07 (0.34)	[-0.04, 0.18]	0.02 (0.15)	[-0.02, 0.07]
AUDIT	8.99 (6.07)	[7.67, 10.31]	13.21 (5.41)	[11.53, 14.90]	4.76 (2.95)	[3.84, 5.68]
Occasions consuming six or more drinks*	1.60 (0.98)	[1.38, 1.81]	2.43 (0.50)	[2.27, 2.58]	0.76 (0.53)	[0.60, 0.93]
Drinks per hour**	2.45 (1.05)	[2.22, 2.68]	3.15 (0.69)	[2.94, 3.37]	1.75 (0.88)	[1.48, 2.02]
Drinks per week**	7.76 (7.20)	[6.20, 9.33]	11.52 (8.25)	[8.95, 14.09]	4.00 (2.81)	[3.13, 4.88]
Percentage drunkenness**	33.23 (33.55)	[25.95, 40.51]	53.44 (30.30)	[44.00, 62.88]	13.02 (22.89)	[5.89, 20.16]

Table 2. Mean inhibition trial accuracy (represented as the proportion of successful inhibitions), go trial accuracy (represented as the proportion of successful sub-400ms responses), go trial reaction time (RT), and failed inhibition trial RT as a function of trial condition for binge (n = 42) and control (n = 42) groups.

	Neutral20		Reward20		Neutral40		Reward40	
	M (*SD*)	95% CI	*M* (*SD*)	95% CI	*M* (*SD*)	95% CI	*M* (*SD*)	95% CI
Inhibition trial accuracy								

Binge	0.29 (0.28)	[0.20, 0.38]	0.22 (0.23)	[0.15, 0.30]	0.44 (0.32)	[0.34, 0.54]	0.40 (0.28)	[0.31, 0.48]
Control	0.50 (0.28)	[0.42, 0.59]	0.33 (0.25)	[0.25, 0.41]	0.62 (0.29)	[0.53, 0.71]	0.52 (0.26)	[0.44, 0.60]
Go trial accuracy								
Binge	0.43 (0.15)	[0.38, 0.48]	0.55 (0.12)	[0.51, 0.59]	0.30 (0.17)	[0.25, 0.36]	0.39 (0.15)	[0.34, 0.43]
Control	0.39 (0.15)	[0.34, 0.43]	0.55 (0.14)	[0.51, 0.60]	0.27 (0.16)	[0.22, 0.32]	0.42 (0.16)	[0.37, 0.47]
Go trial RT (ms)								
Binge	328.82 (41.63)	[315.84, 341.79]	331.10 (38.12)	[319.22, 342.98]	331.38 (41.97)	[317.78, 344.99]	335.84 (41.06)	[322.88, 348.00]
Control	351.74 (46.17)	[337.16, 366.31]	345.80 (44.19)	[331.85, 359.75]	354.36 (47.03)	[339.32, 369.40]	361.75 (45.71)	[347.51, 376.00]
Failed inhibition trial RT (ms)								
Binge	321.12 (86.82)	[292.98, 349.27]	331.13 (53.68)	[313.73, 348.53]	294.63 (118.42)	[256.24, 333.02]	289.78 (107.96)	[254.78, 324.77]
Control	323.89 (99.81)	[290.61, 357.17]	331.28 (53.68)	[308.34, 354.23]	332.43 (120.19)	[292.36, 372.51]	337.15 (93.17)	[306.08, 368.21]

Table 1: Legend

NART IQ = National Adult Reading Test predicted IQ. DAST = Drug Abuse Screening Test score. FTND = Fagerström Test for Nicotine Dependence score. AUDIT = Alcohol Use Disorders Identification Test total score. Drinks refers to self-reported alcohol consumption in Australian standard drinks (1 drink = 10 g alcohol). CI = confidence interval.

* Participants were asked to consider drinking occasions over the preceding twelve months.

** Participants were asked to consider standard weeks in the preceding six months.