The involuntary nature of binge drinking: goal directedness and awareness of intention

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ABSTRACT

Binge drinking represents a public health issue and is a known risk factor in the development of alcohol use disorders. Previous studies have shown behavioural as well as neuroanatomical alterations associated with binge drinking. Here, we address the question of the automaticity or involuntary nature of the behaviour by assessing goal-directed behaviour and intentionality. In this study, we used a computational two-step task, designed to discern between model-based/goal-directed and model-free/habitual behaviours, and the classic Libet clock task, to study intention awareness, in a sample of 31 severe binge drinkers (BD) and 35 matched healthy volunteers. We observed that BD had impaired goal-directed behaviour in the two-step task compared with healthy volunteers. In the Libet clock task, BD showed delayed intention awareness. Further, we demonstrated that alcohol use severity, as reflected by the alcohol use disorders identification test, correlated with decreased conscious awareness of volitional intention in BD, although it was unrelated to performance on the two-step task. However, the time elapsed since the last drinking binge influenced the model-free scores, with BD showing less habitual behaviour after longer abstinence. Our findings suggest that the implementation of goal-directed strategies and the awareness of volitional intention are affected in current heavy alcohol users. However, the modulation of these impairments by alcohol use severity and abstinence suggests a state effect of alcohol use in these measures and that top-down volitional control might be ameliorated with alcohol use cessation.

Keywords   alcohol dependence, binge drinking, goal-directed behaviour, habitual behaviour, intention awareness.

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INTRODUCTION

Binge drinking is characterized by consuming large quantities of alcohol (blood alcohol concentration ≥ 80 mg%) in a short period of time (about 2 hours) followed by longer periods of abstinence. It has numerous negative social and individual consequences and is a prominent risk factor for the development of alcohol abuse disorders (Crabbe, Harris & Koob 2011). Binge drinking has been associated with attentional impairments, decreased sensitivity to the anticipation of high-risk negative outcomes and increased premature responding and trait impulsivity (Bauer & Ceballos 2014; Sanchez-Roige *et al.* 2014; Worbe *et al.* 2014; Morris, Kundu, Baek, *et al.* 2016a). Neuroimaging has further revealed grey matter

abnormalities within ventral striatum (VS), prefrontal cortex (PFC) and limbic areas in binge drinkers (BD) (Howell *et al.* 2013; Doallo *et al.* 2014; Mashhoon *et al.* 2014), as well as PFC hyperactivity following high-risk decisions (Worbe *et al.* 2014), but hypoactivity during working memory tasks (Crego *et al.* 2010). Several lines of evidence suggest potential abnormalities in involuntary automatic behaviours in addictions, from a shift away from goal-directed behaviours and relapse triggers from incentive cues. Here, we assess the relationship between goal-directed behaviours and motor intention in severe BD.

Dual-system accounts suggest that action control is determined by the balance between goal-directed or model-based behaviour, driven by response–outcome

information, and habitual or model-free behaviour, driven by stimulus–response associations (Gläscher *et al.* 2010; van der Meer & Redish 2010; de Wit *et al.* 2012; Dolan & Dayan 2013). Overreliance on habits over model-based behaviour has been reported in a number of neuropsychiatric disorders, including chronic addiction (Gillan *et al.* 2011; Hogarth, Chase & Baess 2012; Sjoerds *et al.* 2013; Gillan *et al.* 2014; Voon, Derbyshire, *et al.* 2015b). Furthermore, anatomical, functional and connectivity studies have evidenced an overlap between the neural substrate of the model-based and model-free systems, which involves lateral and ventromedial PFC, orbitofrontal cortex, inferior parietal cortex (IPC) and striatum (Valentin, Dickinson & O'Doherty 2007; Tanaka, Balleine & O'Doherty 2008; de Wit *et al.* 2009; Gläscher *et al.* 2010; de Wit *et al.* 2012; Voon, Derbyshire, *et al.* 2015b; Morris, Kundu, Dowell, *et al.* 2016b), and the structures altered in BD (Howell *et al.* 2013; Vargas *et al.* 2014; Whelan *et al.* 2014; Worbe *et al.* 2014; Morris, Kundu, Baek, *et al.* 2016a).

It has been shown that alcohol dependence affects the ability to base behaviour on response–outcome information (Sjoerds *et al.* 2013), which is at the core of model-based behaviour. A further study showed that heavy drinkers, including alcohol-dependent subjects, showed increased alcohol cue reactivity in the dorsal striatum, whereas light social drinkers showed increased VS and PFC activities (Vollstädt-Klein *et al.* 2010), suggesting a shift from ventral to dorsal striatal involvement, such as that seen in the development of addiction, and from goal-directedness to habitual behaviour (Corbit, Nie & Janak 2012; Everitt & Robbins 2013). Similarly, alcohol-dependent subjects tested early in abstinence showed impaired model-based behaviours tested using the two-step task (Sebold *et al.* 2014). However, this bias towards model-free behaviour in alcohol-dependent individuals has been reported to decrease with prolonged abstinence, suggesting a possible role for top-down volitional control in increasing goal directedness (Voon, Derbyshire, *et al.* 2015b). We have also previously shown that BD take more risks when anticipating loss outcomes. The behaviour shifts towards a more risk-averse attitude when exposed explicitly to the actual loss outcome, suggesting potentially that the explicit nature of experiencing the loss might counteract underlying automatic biases towards risk (Worbe *et al.* 2014).

Model-based behaviour involves active deliberation and prospective planning in order to direct actions towards desirable outcomes (Gläscher *et al.* 2010; van der Meer & Redish 2010; de Wit *et al.* 2012; Dolan & Dayan 2013). Therefore, the fact that individuals drink excessively or go in drinking binges, despite their negative consequences (Crabbe *et al.* 2011), appears to contradict successful goal-directed behaviour. Furthermore, this

ability to prospectively track motivationally relevant outcomes most probably also requires a certain level of volitional awareness, more specifically, of both the planning or intention to act and the action itself.

Intention awareness has been extensively studied in the field of motor intention. Libet *et al.* (1983) designed a task aimed at discerning between the awareness of the intention to move and of the movement itself, showing that the former (W judgement) occurred around 200 milliseconds before the latter (M judgement). Although their task has been subject to some criticism (Gomes 1998; Danquah, Farrell & O'Boyle 2008), numerous studies have replicated the basic findings of the original study (Lau *et al.* 2004; Walsh *et al.* 2010; Fried, Mukamel & Kreiman 2011). Anatomically, intention awareness has been reported to involve supplementary motor complex, lateral PFC and IPC (Fried *et al.* 1991; Lau *et al.* 2004; Fried *et al.* 2011; Desmurget & Sirigu 2012), thus sharing part of the neural substrate of model-based behaviour.

The interval between W and M judgements can be used as an implicit measure of conscious awareness of volitional intention, and it has been argued that this interval would allow for intentional stopping or vetoing of the movement (Libet 1999; Haggard & Libet 2001). Several neuropsychiatric disorders have been associated with delayed awareness of motor intention (Edwards *et al.* 2011; Moretto *et al.* 2011; Tabu *et al.* 2015; Baek *et al.* in press), reflected as a reduced veto period or a shift of the W towards the M judgement. Moreover, this veto period might be used not only to stop the initiated movement but also to evaluate whether the selected action might be optimal to obtain the desired effect (Haggard & Libet 2001). As stated previously, optimal action selection is paramount to goal-directed behaviour. Interestingly, at least two of the disorders associated with reduced W–M intervals, Parkinson's disease and Tourette's syndrome, have also been associated with alterations in model-based and model-free behaviours (Marsh *et al.* 2004; de Wit *et al.* 2011; Hadj-Bouziane *et al.* 2013; Wylie *et al.* 2013), further supporting the notion that maintaining optimal balance between these two systems might require a certain level of intention awareness.

In the current study, we aimed to study goal-directed behaviour and intention awareness in BD and healthy volunteers (HV). To this end, we used a two-step task (Daw *et al.* 2011), specifically designed to computationally differentiate model-free and model-based behaviours, as well as the Libet clock task (Libet *et al.* 1983). We hypothesized that BD subjects with current ongoing heavy alcohol use would have lower goal-directed learning compared to HV. We further hypothesized that BD would be impaired in intention awareness relative to HV.

MATERIALS AND METHODS

Participants

Thirty-one BD (12 women, 21.29 ± 2.52 years old) and 35 HV (20 women, 23.17 ± 2.83 years old) aged between 19 and 29 years were recruited from community and university-based advertisements. Both groups were gender matched, $\chi^2 = 2.24$, $P > 0.1$, and age matched within 5 years, but the healthy controls were slightly older as a group, $t_y(51) = -3.22$, $d = 0.70$, $P = 0.002$.

Binge-drinking criteria were based on the National Institute on Alcohol Abuse and Alcoholism diagnostics that define consumption of greater than eight units for men or six units for women within a 2-hour period at least once a week for the previous 6 months (National Institute on Alcohol Abuse and Alcoholism 2004, Winter). Subjects also had to have the intention to get drunk and also have been drunk at least once per week for the previous 6 months. They were excluded if they had a major psychiatric disorder, substance addiction or medical illness or were on psychotropic medications. Psychiatric disorders were screened with the mini-international neuropsychiatric interview (Sheehan *et al.* 1998), and participants completed the National Adult Reading Test to assess verbal IQ (BD: $M = 116.69$, $SD = 4.03$, $n = 26$; HV: $M = 115.47$, $SD = 5.66$, $n = 32$; effect of group: $P > 0.1$; effect of the age covariate: $P > 0.1$), the Beck Depression Inventory to assess depressive symptoms (BD: $M = 9.54$, $SD = 8.01$, $n = 26$; HV: $M = 7.29$, $SD = 7.48$, $n = 34$; effect of group: $P > 0.1$; effect of the age covariate: $P > 0.1$) and the Alcohol Use Disorders Identification Test (AUDIT) (BD: $M = 16.08$, $SD = 5.32$, $n = 26$; HV: $M = 4.53$, $SD = 3.34$, $n = 34$; effect of group: $F(1) = 86.33$, $P < 0.001$; effect of the age covariate: $P > 0.1$) and the Alcohol Use Questionnaire to assess alcohol use severity (BD: $M = 33.41$, $SD = 14.25$, $n = 22$; HV: $M = 8.87$, $SD = 8.90$, $n = 27$; effect of group: $F(1) = 57.35$, $P < 0.001$; effect of the age covariate: $P > 0.1$). The mean number of times drunk over the last 6 months was greater for BD (BD: $M = 20.70$, $SD = 14.25$, $n = 23$; HV: $M = 2.21$, $SD = 4.21$, $n = 34$; effect of group: $F(1) = 63.29$, $P < 0.001$; effect of the age covariate: $P > 0.1$). Subjects were questioned on their patterns of alcohol consumption, to ensure they fit the criteria, and their last alcohol binge prior to testing was recorded. Subjects were administered a breathalyser test on the day of the study.

Participants were tested on two separate days, with the two-step task tested on day 1 and the Libet clock and working memory tasks tested on day 2. All subjects provided written informed consent before enrolling and were compensated for their time. The study was approved by the University of Cambridge Research Ethics Committee.

### Task description

Two-step task

Participants performed the two-step task as described in our previous work (Fig. 1a) (Voon, Derbyshire, *et al.* 2015b). In stage 1, participants had to choose between two stimuli, each of which led to one of the two stimulus pairs with a fixed probability ($P = 0.70$) and to the other stimulus pair with opposite probability ($P = 0.30$). The stimulus choice made in stage 2 led to a reward with probability varying slowly and independently over time between 0.25 and 0.75. Each of the four stimuli in stage 2 was attached to a different probability distribution, and the association between each stage 2 stimulus and its reward probability was counterbalanced across participants. Choices at each stage had to be made within 2 seconds, and the result of each choice was presented after 1.5 seconds. The stimulus chosen in stages 1 and 2 remained on screen as a reminder in stage 2 and the outcome stage, respectively. If the stage 2 choice was rewarded, participants saw a £1 coin for 1 second; otherwise, they saw a grey circle for 1 second.

The task consisted of three blocks of 67 trials. Prior to the task, participants underwent extensive computer-based instructions, which included explanatory examples of changes in transition and probability, and a short block of 50 trials in the same format as the experimental task but with different stimuli. The task was run with Cogent 2000 (http://www.vislab.ucl.ac.uk/cogent.php) on Matlab R2011a (MathWorks, Natick, USA).

Libet's clock task

In a separate session, participants also performed the Libet clock task (Fig. 1b) (Libet *et al.* 1983). In each trial, a hand revolved inside a clock face marked at 5-minute intervals at 2560 milliseconds per cycle. Participants were instructed to make a button press with their right index finger after a random time interval. They were asked to act as spontaneously as possible and to avoid preselecting a position of the hand to trigger the button press.

Participants were required to make either a W judgement or an M judgement. In W judgement trials, they were instructed to pay attention to when they first felt the urge to press the button; in M judgement trials, they were instructed to pay attention to when they actually pressed the button. After the button press, the clock hand continued rotating for 1500–2500 milliseconds. Participants then verbally reported its position either where
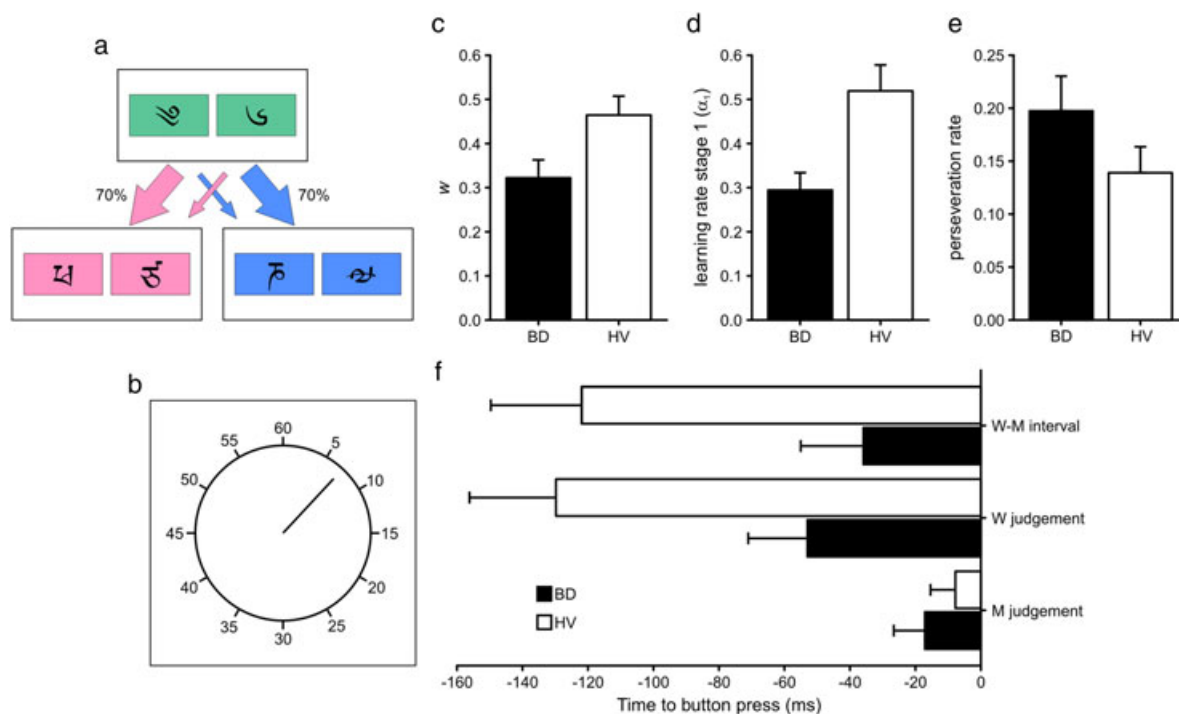
Figure 1 Results from the analysis of the two-step and Libet clock tasks. *Schematic* depiction of the (a) two-step and (b) Libet clock tasks. Mean (c) weighting parameter (*w*), (d) learning rate in stage 1 (α_1) and (e) perseveration rate from the two-step task. (f) Mean estimated times of intention (W judgement), movement (M judgement) and difference between intention and movement (W–M) relative to the recorded button press from the Libet clock task. Black bars represent binge drinkers (BD) and white healthy volunteers (HV). Error bars represent the standard error of the mean [Colour figure can be viewed at wileyonlinelibrary.com]

they first felt the urge to press the button or when they actually pressed it, depending on the type of trial.

The task consisted of one M judgement block followed by a W judgement block, each consisting of 20 trials. The programme was developed with LabView (National Instruments, Austin, TX, USA).

Memory tests

In order to control for possible working memory effects in the two-step task, we also tested participants with the spatial working memory (SWM) and paired associates learning (PAL) tasks of the Cambridge Neuropsychological Test Automated Battery (http://www.cambridgecognition.com/technology).

Statistical analysis

For the two-step task, choice behaviour was fit to a computational model, which learned action values through both model-based reinforcement learning and model-free State-Action-Reward-State-Action (SARSA) (λ) temporal difference learning. Participants' choices were driven by the weighted combination of these two types of learning, with the relative weighting controlled by a free parameter *w*, which was used as a measure of the reliance on model-free (*w* = 0) or model-based (*w* = 1) strategies. Additional

behavioural measures were the indices of choice reliability in each stage (β), the learning rate in each stage (α), the reinforcement eligibility parameter (λ) and the perseveration rate (for further information on the model and the equations used, see Daw *et al.* 2011; Voon, Baek, *et al.* 2015a). We also examined the behavioural parameters of model-based (interaction between transition and outcome) and model-free (effect of outcome) measures. Each parameter was analysed by means of analysis of covariance (ANCOVA) to test for differences between BD and HV, while controlling for the effect of the age covariate.

For Libet's clock task, average latencies (excluding values over/under 3 *SD*) were computed for each participant's W and M judgements. Latencies were introduced in a 2 × 2 model to test for the effects of group and type of judgement and using age as a covariate. The difference between W and M judgements (W–M interval) was used as an implicit measure of conscious awareness of volitional intention. This measure was tested using an ANCOVA with age as a covariate.

The relationship between test outcomes (*w*, model-free and model-based scores from the two-step task, and W–M interval from the Libet clock task) and alcohol use severity, as reflected by AUDIT score, was subsequently tested on an exploratory basis. To this end, variables were introduced in regression models. If AUDIT score

significantly predicted the behavioural measure, the Fisher r-to-z transformation was used to assess the significance of the difference between the correlation coefficients of BD and HV. Further, k-means clustering was performed to test whether the days since the last binge drinking episode had an influence on the behavioural measures in the BD group. This method was chosen over regression because of the limited number of data points in the time variable.

Task outcomes were analysed using R (https://www.r-project.org/). Data that did not conform to normality of distribution and/or had outliers were tested using robust statistical methods (Yuen's t-test with 10 percent winsorization, robust rank-based ANCOVA and least trimmed squares regression). Otherwise, parametric testing was used (linear regression). k-means clustering used the Calinski–Harabasz index to estimate the number of clusters, with a maximum of 10 iterations and two clusters, given the reduced number of data points; the Duda–Hart test with a significance level of $P = 0.005$ was applied to assess whether the data set should be split into clusters.

RESULTS

Two-step task

Thirty BD and 35 HV completed the two-step task. One BD did not complete this task.

After controlling for the effect of age, BD ($M = 0.322$, $SD = 0.224$) had significantly lower w scores than HV ($M = 0.464$, $SD = 0.255$), $F(1) = 5.03$, $P = 0.029$ (Fig. 1c); the age covariate was not significantly related to the w score, $P > 0.1$. However, when analysing the model-based and model-free scores separately, measures that are less robust than the computational analysis, there were no differences between groups in either score, $P > 0.05$, nor was the age covariate related to the scores, $P > 0.05$.

There were no significant differences in choice reliability in stage 1 (β_1) between BD ($M = 4.63$, $SD = 2.97$) and HV ($M = 5.69$, $SD = 3.78$), $P > 0.05$, but there was a significant relationship between this parameter and the age covariate, $F(1) = 6.43$, $P = 0.014$. There were no differences in choice reliability in stage 2 (β_2), nor was this parameter related to the age covariate, $P > 0.1$.

After controlling for the effect of age, BD ($M = 0.294$, $SD = 0.217$) also had significantly lower learning rates in stage 1 (α_1) than HV ($M = 0.519$, $SD = 0.348$), $F(1) = 4.68$, $P = 0.034$ (Fig. 1d); but there was no relationship between α_1 and participants' age, $P > 0.1$. There were no differences between the groups' learning rates in stage 2 (α_2), nor was this parameter related to the age covariate, $P > 0.1$.

Binge drinkers ($M = 0.197$, $SD = 0.180$) had significantly higher perseveration rates than HV ($M = 0.139$, $SD = 0.145$) after controlling for the effect of age, $F(1) = 4.21$, $P = 0.044$ (Fig. 1e); but age was not related to perseveration rates, $P > 0.1$.

There were no significant differences between groups in the λ parameter, nor was this parameter related to the subjects' age, $P > 0.1$.

Libet's clock task

Twenty-two BD and 31 HV completed the Libet clock task. Nine BD and four HV did not complete this task, which was tested on a separate day.

The robust ANCOVA performed on the latencies of the W and M judgements showed the main effects of the group, $F(1) = 5.40$, $P = 0.022$, and condition, $F(1) = 18.31$, $P < 0.001$, and an interaction between the group and condition, $F(1) = 5.73$, $P = 0.018$, after controlling for the effect of age. The age covariate had no relationship with the latencies of the W and M judgements, $P > 0.05$. Šidák-corrected post hoc t-tests showed that BD ($M = -53$ milliseconds, $SD = 85$) made the W judgement marginally closer to the actual movement than HV ($M = -130$ milliseconds, $SD = 147$), $t_y(41) = 2.15$, $d = 0.61$, $P = 0.074$, whereas there were no differences in the latencies of the M judgement (BD: $M = -17$, $SD = 45$; HV: $M = -8$, $SD = 42$), $P > 0.1$.

After controlling for the effect of age, the critical difference between W and M judgements (W–M interval) was marginally shorter in the case of BD ($M = -36$ milliseconds, $SD = 90$) than in the case of HV ($M = -122$ milliseconds, $SD = 155$), $F(1) = 4.00$, $P = 0.051$, while the age covariate was not significantly related to the W–M interval, $P > 0.1$ (Fig. 1f).

Memory

Twenty-one and 22 BD completed the SWM and PAL tasks, respectively, and 23 HV completed both tasks.

After controlling for the effect of age, there were no statistical differences between the number of errors committed by BD and HV in the SWM task, $P > 0.1$, but the age covariate was significantly related to the number of errors, $F(1) = 6.53$, $P = 0.014$. There were neither differences between the number of errors committed by the groups in the PAL task nor an effect of the age covariate, $P > 0.05$.

Relationship with clinical variables

On an exploratory basis, we further examined the relationship between the main outcomes and clinical variables. Regarding the Libet clock task, AUDIT score significantly predicted the length of the W–M interval

(Fig. 2a), $F(1, 47) = 4.96$, $r_{lts} = 0.31$, $P = 0.031$, with greater alcohol use severity predicting shorter to inverted W–M intervals. AUDIT score significantly predicted the length of the W–M interval in the BD group, $F(1, 19) = 4.82$, $r_{lm} = 0.45$, $P = 0.041$, with greater alcohol use severity predicting shorter to inverted W–M intervals. However, AUDIT score was uncorrelated to W–M length in HV, $F(1, 26) = 0.63$, $r_{lts} = -0.15$, $P > 0.1$. The difference between the correlation coefficients of both groups was also statistically significant, $z = 2.14$, $P = 0.032$.

There was no relationship between AUDIT and either w, model-free or model-based scores from the two-step task, $P > 0.1$.

Twenty-two BD responded to the question regarding the days elapsed since their last binge. k-means clustering showed that subjects that had had the last binge drinking episode under 4 days prior to testing had lower w ($M = 0.278$, $SD = 0.229$; Fig. 2b), as well as higher model-free ($M = 0.120$, $SD = 0.097$; Fig. 2c) and lower model-based ($M = 0.025$, $SD = 0.088$; Fig. 2d) scores than those that had had the last episode over 4 days before testing (w: $M = 0.483$, $SD = 0.238$; model-free: $M = 0.052$, $SD = 0.071$; model-based: $M = 0.157$, $SD = 0.096$), $P = 0.002$, $P = 0.001$ and $P = 0.001$, respectively.

The time since the last drinking binge had no influence on the W–M interval from Libet's clock task.

DISCUSSION

In the current study, we explore model-based behaviour and intention awareness in BD and HV. Our BD sample shows particularly severe binge drinking behaviour, as they were only included in the study if they fit National Institute on Alcohol Abuse and Alcoholism criteria and
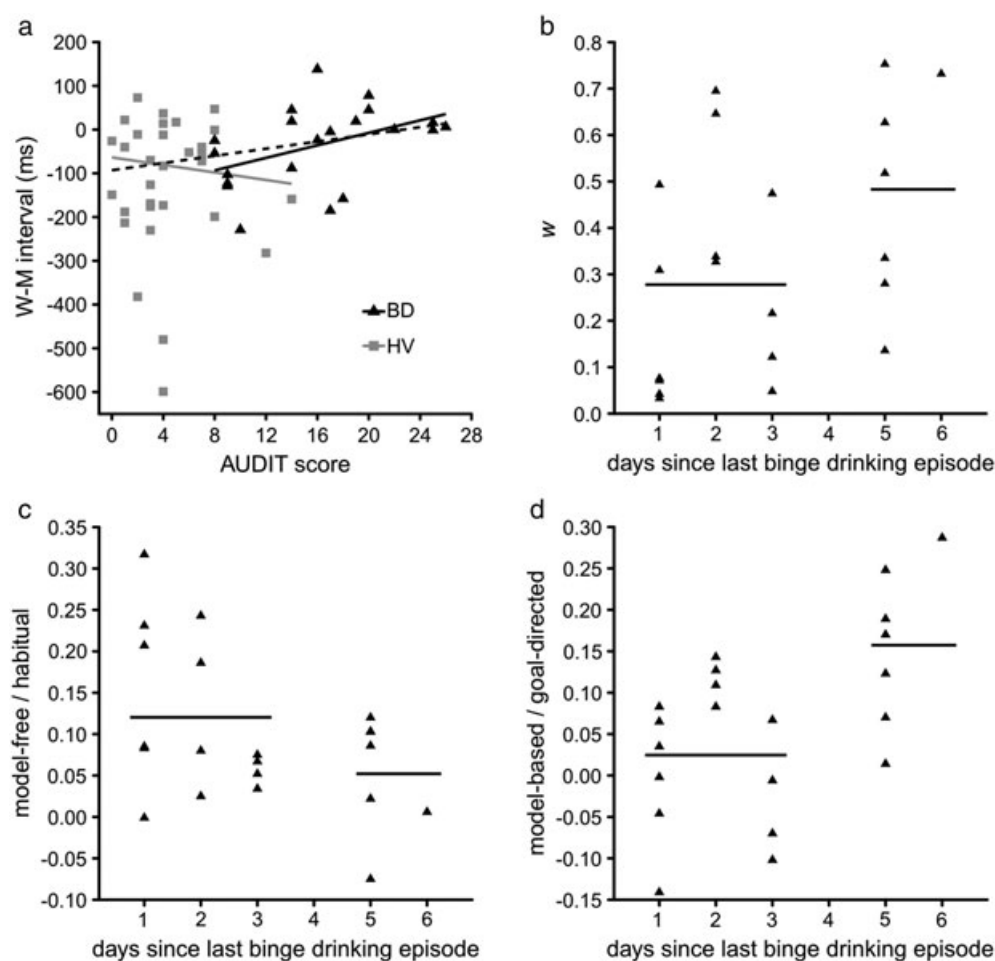
Figure 2 Results of the regression and cluster analyses. (a) Relationship between AUDIT score and W–M difference. Results of the cluster analysis of the (b) weighting parameter (w), (c) model-free and (d) model-based scores based on the days since the last binge drinking episode of the binge drinkers (BD). Horizontal lines represent the mean score of each cluster. BD are represented by black triangles and solid lines, healthy volunteers (HV) are represented by grey squares and solid lines and the regression line from the analysis over all subjects is represented by a black dashed line

further had been drunk at least once per week for the previous 6 months. The two-step task (Daw *et al.* 2011) is used to differentiate between model-based goal-directed behaviour and model-free habitual behaviour. In this task, BD show significantly lower *w* scores than HV, indicating a bias away from model-based behaviours towards habitual behaviour. BD also showed lower learning rates than HV in stage 1 of the task, but not in stage 2. Once age was controlled for, we further show that BD have greater perseverative deficits, suggesting not only a tendency towards selecting the same previously rewarded action but also a greater tendency towards selecting the same stage 1 option irrespective of the outcome. The Libet clock task (Libet *et al.* 1983) is used to discriminate intention from movement awareness. Our findings indicate that, whereas M judgements are comparable between groups, the latency of the W or intention judgement in BD is shifted towards movement onset. Similarly, the W–M interval, an implicit measure of conscious awareness of volitional intention, is significantly reduced in BD than in HV. Crucially, we show that clinical variables appear to influence these measures in BD, with greater alcohol use severity predicting decreased conscious awareness of volitional intention and model-freeness decreasing with the number of days after a binge episode.

A similar tendency towards habitual learning to the one observed here in BD has been previously observed in patients with obsessive–compulsive disorder, methamphetamine addicts and subjects with binge eating disorder (Voon, Derbyshire, *et al.* 2015b). However, studies with alcohol-dependent individuals have offered inconsistent results. Sjoerds *et al.* (2013) reported impaired goal-directed learning in alcohol-dependent subjects using an instrumental learning task. Following overtraining on stimulus–response–outcome contingencies, subjects underwent an outcome-devaluation test. The impairment in goal-directed learning in alcohol-dependent subjects was associated with decreased activity in the ventromedial PFC and anterior putamen, and increased activity in posterior putamen (Sjoerds *et al.* 2013). Using the two-step task, Sebold *et al.* (2014) showed impaired model-based behaviours in alcohol-dependent subjects tested early in abstinence (2 weeks). However, Voon, Derbyshire, *et al.* (2015b) did not find differences between alcohol-dependent subjects and HV, which may be related to the timing of testing, as they showed that *w* scores increased with abstinence duration (2 weeks to 1 year), suggesting an improvement in goal-directed behaviour with abstinence. In the current study, we observe that those BD who had been abstinent for longer had higher *w* and model-based scores, and lower model-free scores than the rest of the group. Together, these findings

suggest that individuals with current heavy alcohol use and binge drinking behaviours rely less on goal-directed behaviours. The fact that abstinence and the number of days after a binge episode improve these scores points to a state effect of alcohol use on this measure.

Our BD sample further displayed significantly reduced W–M intervals compared with HV, suggesting an altered experience of volition. Similar results have been described in disorders of the basal ganglia (Moretto *et al.* 2011; Tabu *et al.* 2015), stroke lesions of the IPC (Sirigu *et al.* 2004) and functional neurological disorder (Edwards *et al.* 2011; Baek *et al.* in press), but to our knowledge, intention awareness had not yet been explored in relation to alcohol use disorders. Furthermore, our data show that alcohol use severity in BD is associated with poorer intention awareness.

There are several plausible mechanisms by which both of these processes may be impaired. We show that working memory is unlikely to be playing a role. Similarly, non-specific attentional deficits would be likely to influence attention to both W and M measures, whereas these findings are specific to a shift in W in the BD group. Impairments in inhibitory control are common in substance use disorders and may be relevant across both tasks. The relevance of the interval between the awareness of intention and movement has been highlighted in the veto hypothesis (Libet 1999; Haggard & Libet 2001), which suggests that the 200 milliseconds interval between W and M can be used to evaluate and change or stop the initiated movement. Therefore, the W–M interval allows for the implementation of cognitive control mechanisms, which are required to avoid impulsive or compulsive acts (Bari & Robbins 2013) and execute goal-directed behaviour. These findings also build on studies focusing on impaired awareness in substance use disorders on multiple levels, including awareness of emotional states, autonomic and bodily signals, error monitoring, awareness of deficits and behavioural choices, and higher-order metacognitive judgements of confidence. Methamphetamine-dependent subjects show elevated alexithymia or impaired emotional awareness, with an abnormal relationship with dopamine receptor availability in the anterior insula and anterior cingulate relative to healthy controls (Okita *et al.* 2016). The role of the anterior insula, implicated in conscious awareness of bodily and autonomic signals, is relevant to addictions (Verdejo-García, Clark & Dunn 2012; Paulus & Stewart 2014; Stewart *et al.* 2014) and has been implicated in stroke lesion studies (Naqvi *et al.* 2007), hypoactivity during cognitive control and negative emotions, and decreased anterior insular volumes (Senatorov *et al.* 2015). Impairments in self-monitoring of error awareness have been related to hypoactivity in the anterior

cingulate and insula (Hester, Nestor & Garavan 2009). Impairments in higher-order metacognitive self-awareness were shown with cocaine use disorder with impairments in the relationship between a visuospatial accuracy task and self-reported confidence associated with decreased grey matter volume in the rostral anterior cingulate (Moeller et al. 2016). Deficits in self-awareness of specific behaviours correlated with different brain regions; thus, impaired self-awareness of apathy was associated with grey matter volume in the dorsal striatum, impulsivity with the orbitofrontal cortex and executive functioning with dorsolateral PFC in addiction (Moreno-López et al. in press). Similar to our findings, impairments in self-awareness improve with abstinence, including insight into the concordance between objective and subjective choices of drug-related and non-drug-related cues (Moeller et al. 2010), self-deception (Martínez-González et al. 2016) and deficits in self-awareness of frontal executive function (Verdejo-García & Pérez-García 2008).

Research suggests a partial overlap between the networks underlying intention awareness and goal-directed behaviour, including lateral PFC and IPC (Lau et al. 2004; Sirigu et al. 2004; Gläscher et al. 2010) for goal-directed behaviour and supplementary motor complex for habitual behaviours (Morris, Kundu, Dowell, et al. 2016b). The decrease in cognitive control implied by our data might be related to frontal anomalies observed in BD (Jacobus et al. 2009; McQueeny et al. 2009; Squeglia et al. 2012; Doallo et al. 2014; Vargas et al. 2014). Although partially reversible (Sullivan et al. 2005; Makris et al. 2008), the pernicious effects of alcohol on these structures are widely acknowledged. Both human and animal models have demonstrated that binge drinking compromises white matter fibre integrity in frontal and temporal regions (Jacobus et al. 2009; McQueeny et al. 2009; Vargas et al. 2014). Moreover, BD have been shown to have increased grey matter volumes in the VS (Howell et al. 2013), influenced by gender (Kvamme et al. 2016), and dlPFC (Doallo et al. 2014), and decreased cortical thickness in cingulate areas (Mashhoon et al. 2014). We have also recently shown that orientation dispersion index, a diffusion measure that putatively marks complexity of dendritic branching, in the same BD population under study demonstrates lower orientation dispersion index in regions implicated in higher-order processing such as the dlPFC and parietal cortex and higher in the VS (Morris et al. in press). PFC input has been proven essential for both successful goal-directed behaviour (Valentin et al. 2007; Tanaka et al. 2008; de Wit et al. 2009; Gläscher et al. 2010) and intention awareness (Lau et al. 2004), with model-based learning further associated with efficient fronto-striatal connectivity (de Wit et al. 2012; Morris, Kundu, Dowell, et al. 2016b).

From the perspective of action control, similar impairments in motor intention using the Libets clock task have been shown with Parkinson's disease, Tourette's syndrome and functional neurological disorders. These disorders are characterized by impaired self-agency, or the sense of the loss of control over self-generated actions. In particular, intriguing similarities may underlie the preceding sensory urge and associated motor tic in Tourette's syndrome and may provide insight into drug cue-related urges triggered by sensory cue stimuli and subsequent motor (e.g. habitual or motivational) behaviour. The premonitory urge in Tourette's syndrome is involuntary and is commonly experienced as an involuntary sensory phenomenon (Cavanna et al. in press), and the tic itself has features of a voluntary movement in that its timing and decision to perform the tic movement in response to the urge can be controlled. A proportion of tics are preceded by a movement potential, a brain potential seen preceding voluntary movement, suggesting that tics have mixed features of voluntary and involuntary movements. The urge in tic disorders is similarly associated with activity in the anterior insula and anterior cingulate along with the supplementary motor area and parietal cortex (Bohlhalter et al. 2006; Lerner et al. 2007). A study focusing on the temporal generation of the urge demonstrated that the urge was associated with cortical activity at 2 seconds before the tic (supplementary motor area, primary sensory cortex and parietal cortex) and engaging subcortical regions 1 second before the tic (anterior cingulate cortex, putamen, insula, amygdala, cerebellum and occipital cortex) (Neuner et al. 2014). Tourette's syndrome has also been linked with lower gamma-aminobutyric acid concentration in the sensory motor cortex along with decreased cortical thickness over the sensorimotor, insular and anterior cingulate cortices linked to the strength of premonitory urges (Draganski et al. 2010; Puts et al. 2015; Draper et al. 2016). Tourette's syndrome is also associated with enhanced habit formation correlating with greater structural connectivity of the supplementary motor cortex and sensorimotor putamen (Delorme et al. 2016).

The current study is not without limitations. Further characterization of the BD population in terms of whether they were hungover and further studies on mechanisms that might link the two including attentional mechanisms would be indicated. How these findings might relate to the literature on impaired awareness in substance misuse and the brain regions implicated would be useful. A prospective study using an alcohol challenge may be indicated.

Binge drinking is characterized by longer periods of abstinence between episodes of alcohol consumption (Courtney & Polich 2009). In the current sample of BD, not only was poorer intention awareness associated with alcohol use severity, but also subjects whose last binge drinking episode took place less than 4 days before testing displayed more model-free habitual and less model-based goal-directed behaviour than those whose last binge drinking episode was more distant. In alcohol-dependent subjects, abstinence has been observed to at least partially reverse some of the effects of alcohol abuse, at both the neuroanatomical and cognitive levels (Petry 2001; Sullivan *et al.* 2005; Makris *et al.* 2008; Voon, Derbyshire, *et al.* 2015b). Moreover, these findings dovetail with prior studies that have shown improvements of model-based behaviours with abstinence in alcohol-dependent subjects (Voon, Derbyshire, *et al.* 2015b). It is particularly interesting that this shift takes place over such a short period of time in BD. However, prior neuroanatomical findings suggest that BD might differ not only from HV but also from alcohol-dependent subjects, with these differences possibly representing early sequelae, the compensatory effects of repeated binge and withdrawal patterns or even trait effects (Howell *et al.* 2013). The relationships observed here between intention awareness and alcohol use severity, and between model-basedness, model-freeness and abstinence suggest that top-down volitional control might be ameliorated with alcohol use cessation.

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Author Contributions

ND is responsible for the data analysis and interpretation, and drafting of the manuscript and figures; DS, KB and PB performed the data acquisition and drafting of the manuscript; and VV is responsible for the study conception and design, interpretation of the data and drafting of the manuscript. All authors have critically reviewed content and approved final version submitted for publication.

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