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Persistence of value-modulated attentional capture is associated with risky alcohol use

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ABSTRACT

Background: This study examined how risky patterns of alcohol use might be related to the persistence of learned attentional capture during reversal of stimulus–reward contingencies.
Methods: Participants were 122 healthy adults (mean age 21 years, 66% female) who completed an assessment including a visual search task to measure value-modulated attentional capture, with a reversal phase following a period of initial training. The assessment also included questions about alcohol use.
Results: Overall, attentional capture was greater for distractors associated with high reward than for those associated with low reward, replicating previous findings of value-modulated attentional capture. When stimulus–reward contingencies were reversed, a higher persistence of learned attentional capture was associated with risky patterns of alcohol use.
Conclusion: This result highlights how value-modulated attentional capture may persist and is associated with risky alcohol use in a non-clinical sample. Future research (potentially with clinical samples of heavy drinkers) aimed towards understanding the mechanisms that drive these reversal deficits, and their relation to other compulsive behaviours, may provide important insights into the development and maintenance of addictive behaviours.

1. Introduction

People who use alcohol and/or other drugs (AODs) heavily, or those who have been diagnosed with a substance use disorder typically show an attentional bias towards stimuli associated with that substance (Field & Cox, 2008; Lubman, Peters, Mogg, Bradley, & Deakin, 2000; Nikolaou, Field, & Duka, 2013). Researchers have argued that such biases form as a result of learning processes, and function to further promote drug-seeking behaviour and problematic AOD use (Berridge, Robinson, & Aldridge, 2009; Field & Cox, 2008). Through repeated pairing of certain stimuli with the rewarding consequences of taking a drug, those previously neutral stimuli are thought to acquire *incentive salience*, subsequently attracting attention and evoking powerful approach responses in their own right (Berridge et al., 2009; Robinson & Berridge, 2000). Research showing that such biases predict AOD use and relapse in people with a substance use disorder (Cox, Hogan, Kristian, & Race, 2002; Marhe, Waters, van de Wetering, & Franken, 2013; Waters et al., 2003), is typically argued to support such theories.

A growing body of research supports the idea that there is variability in the likelihood that individuals will attribute incentive salience to Pavlovian signals of reward, such that these reward-signalling cues come to powerfully modify subsequent behaviour. This behaviour, known as *sign-tracking*, has in turn been viewed as reflecting propensity to develop addictive behaviours (Flagel, Akil, & Robinson, 2009; Robinson & Flagel, 2009). While much of the research on sign-tracking has used animal models, Le Pelley et al. (2015) recently developed a procedure to assess an analogue of sign-tracking in human attention. In this task (illustrated in Fig. 1), participant searched for a diamond target among circles on every trial. The faster they found and responded to this target, the more points they earned (with points converted to money at the end of the experiment). Critically, one of the (nontarget) circles could be coloured, either blue or orange (all other shapes were grey). The colour of this colour-singleton circle—referred to as the *distractor*—influenced the size of the reward available on the current trial: one colour (the high-reward colour) signalled that a large reward was available, and the other (low-reward) colour signalled that a small reward was available. Notably, while the distractor signalled reward magnitude, it was not the target that participants responded to in order to receive that reward; thus distractors had a Pavlovian, but not instrumental, relationship with reward. The key finding was that

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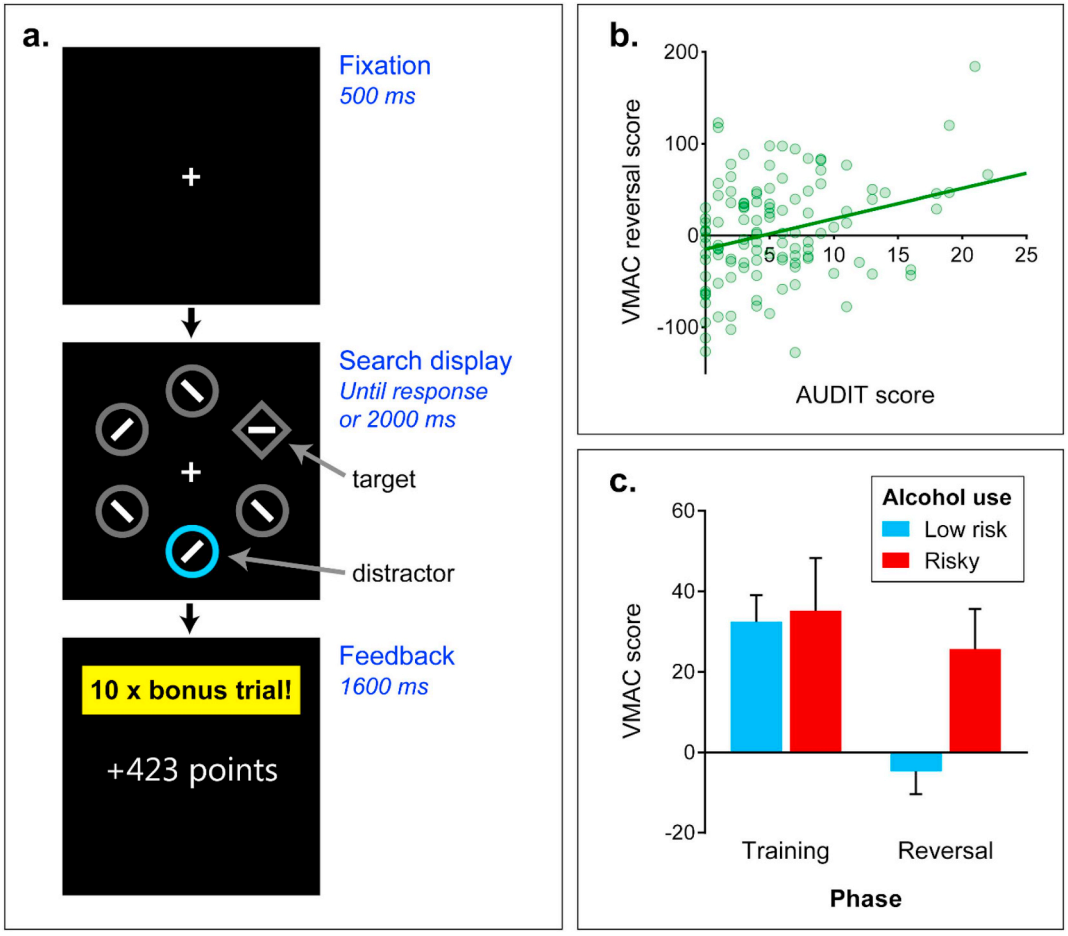

Fig. 1. Sequence of trial events. (a) Participants responded to the orientation of the line segment (horizontal or vertical) within the diamond (target). One of the nontarget circles could be a colour singleton distractor. Fast, correct responses to the target received reward (points), depending on the distractor colour. A high-value distractor colour reliably predicted a bonus reward; a low-value reliably predicted small reward; if no colour singleton was present in the display (distractor-absent trial), then a small reward was given. (b) A scatterplot of vmac-r reversal score (RT for previous high minus RT for previous low) as a function of AUDIT score. (c) Mean response times across reversal phase for low risk (blue) and risky use (red) AUDIT groups. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

responses to the target were significantly slower (but no more accurate) for trials with a high-reward distractor compared to trials with a low-reward distractor. This suggests that the signal of high reward was more likely to capture participants' attention, slowing their response to the target – even though this enhanced capture was counterproductive, because it meant participants earned less on high-reward trials than would otherwise have been the case. We refer to this effect of reward on distraction as *value-modulated attentional capture* (VMAC).

Le Pelley et al.'s (2015) VMAC task provides a measure of the extent to which reward-signals come to influence behaviour. As such we can use it to investigate individual differences in propensity towards 'attentional sign-tracking', and whether these are associated with addiction-related behaviours as suggested by animal models (Albertella et al., 2017). In the current study we considered in particular the persistence—the rigidity—of reward-related attentional biases. Inflexibility of behaviour is characteristic of addiction: even if an individual no longer wants to use drugs and/or expects negative consequences from drug use, drug cues continue to elicit strong attentional biases and cravings (among other conditioned responses). The maladaptive and persistent nature of drug use behaviours, and their susceptibility to be influenced by drug-related stimuli, is a prominent feature of addiction, so much so that it may be considered a compulsive disorder (for reviews, see Everitt & Robbins, 2005; Lubman, Yücel, & Pantelis, 2004). In line with the idea that compulsivity is a core component of addictive behaviours, addiction shares with other compulsive disorders (e.g., obsessive-compulsive disorders) the characteristic condition of cognitive inflexibility; i.e., deficits in reversal learning and/or set-shifting (and abnormalities in brain activation during these tasks) (Fineberg et al., 2014; Fontenelle, Oostermeijer, Harrison, Pantelis, & Yücel, 2011; Izquierdo & Jentsch, 2012).

Studies to date have focused on instrumental/behavioural manifestations of cognitive rigidity. For instance, excessive habit learning is considered a transdiagnostic marker of compulsivity (Gillan, Robbins, Sahakian, van den Heuvel, & van Wingen, 2016), and deficits in adapting learned behaviour to changes in instrumental contingencies are considered key to addiction (Izquierdo & Jentsch, 2012). However, abnormalities in attentional biases and set-shifting indicate that compulsivity may have its roots in earlier processes of attentional processing (as opposed to abnormalities at the response level), such as stimulus prioritisation and/or attentional disengagement (e.g., Fineberg et al., 2014). Further, in line with arguments that suggest cognitive inflexibility or habit propensity as risk markers for compulsivity (Chamberlain et al., 2007; Gillan et al., 2016), individual differences in attentional inflexibility may precede and predispose individuals to developing compulsive disorders, including addiction. Thus, compulsive behaviours—including addiction-related behaviours—may reflect, in part, a predisposition towards an inability to adapt attentional processing according to context or current demands. As a test of this idea, the current study used a variant of Le Pelley et al.'s (2015) VMAC procedure, in which stimulus–reward relationships were reversed following a

period of initial training, to investigate whether risky patterns of alcohol use in a sample of healthy adults are associated with a particularly rigid and inflexible influence of reward on attention.

2. Method

2.1. Ethical approval and participants

Ethical approval was obtained from the UNSW Sydney Human Research Ethics Advisory Panel (Psychology). Participants were 124 UNSW Sydney students who completed the study in a classroom setting. Two participants made fewer than 50% correct responses during the training phase of the visual search task and were excluded from analysis. Thus, 122 participants were included in this study (80 females; age $M = 20.5$ years, SD = 2.15, range 18–30).

2.2. Apparatus, stimuli, and design

Participants completed the study using standard PCs with 23-in. monitors (1920 × 1080 resolution, 60 Hz refresh), positioned ~60 cm from the participant. Stimulus presentation was controlled by MATLAB using Psychophysics Toolbox extensions (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997).

The visual search task used a variant of Le Pelley et al.'s (2015, Experiment 2) VMAC procedure (see Fig. 1a). All stimuli were presented on a black background. Each trial began with a central fixation cross, followed after 500 ms by the *search display*. The search display comprised six shapes (2.3 × 2.3° visual angle) —five circles, and one diamond (the *target*)— arranged evenly around an imaginary ring of diameter 10.1°. One of the circles (termed the *distractor*) could be rendered in either blue or orange, or green and pink; all other shapes were grey. For half of participants, distractor colours were blue and orange; for remaining participants, distractors were green and pink. Assignment of blue/pink and orange/green to the roles of *high-reward* and *low-reward* colours was counterbalanced across participants within each of these groups.

The diamond target contained a white line segment oriented either vertically or horizontally; other shapes contained a similar line segment tilted 45° randomly to the left or right. Participants' task was to report the orientation of the line within the target as quickly as possible—by pressing either the 'C' key (horizontal) or 'M' key (vertical)—with faster responses earning more points. Each trial-block of the task comprised 48 trials: 20 trials featuring a distractor rendered in the high-reward colour, 20 trials with a distractor in the low-reward colour, and 8 distractor-absent trials (in which all shapes were grey), in random order. For correct responses, on low-reward-distractor and distractor-absent trials, participants were awarded 0.1 points for every ms that their response time (RT) was below 1000 ms (so an RT of 600 ms would earn them 40 points). Trials in which the display contained a high-reward distractor were labelled as bonus trials, and points were multiplied by 10 (so an RT of 600 ms would earn 400 points). Correct responses with RT > 1000 ms earned no points, and errors resulted in loss of the corresponding amount. The search display remained on-screen until the participant responded or the trial timed-out (after 2 s). A feedback screen then appeared. On 'standard' (low-reward distractor or distractor-absent) trials, if the response was correct, feedback showed the number of points earned on that trial; if the response was incorrect, feedback showed "ERROR" and the number of points lost; and if the trial timed-out feedback was "TOO SLOW: Please try to respond faster". On bonus (high-reward) trials the corresponding feedback was accompanied by a box labelled "10 × bonus trial!". Inter-trial interval was 1200 ms.

Target location, distractor location, and target line segment orientation (vertical or horizontal) were randomly determined on each trial.

2.3. Procedure

Participants were informed that the aim of the visual search task was to earn as many points as possible. Due to the classroom setting of this study we were unable to give monetary bonuses based on points earned, so as an alternative source of motivation points were used to unlock 'medals' in the current study. For every 11,667 points that participants earned, they unlocked a new medal (in the order bronze, silver, gold, platinum, diamond, and elite). This value of points per medal was set based on mean RTs from Le Pelley et al. (2015), with the aim that the best-performing ~10% of participants would unlock the 'elite' medal.

Participants were informed that (1) the faster they responded (correctly) on each trial, the more points they would earn, (2) that when a circle in the high-reward colour was present in the search display it would be a bonus trial on which points were multiplied by 10, and (3) that when a circle in the low-reward colour was present it would not be bonus trial. Check-questions were used to verify that participants understood these instructions. Participants then completed six trial-blocks (288 trials) in the training phase of the VMAC task, taking a break between blocks; during this break they were shown the total number of points they had earned so far, and an animation presented any additional medals that they had unlocked since the previous break.

Instructions following the training phase told participants that the relationships between the coloured circles and bonus trials had reversed. For example, a participant for whom blue had been the high-reward colour and orange the low-reward colour during training would be told that, from now on, if an orange circle was present in the display it would be a bonus trial, and if a blue circle was present it would not be a bonus trial. Again check-questions were used to verify that participants had read and understood these instructions. Participants then completed a single, 48-trial block in the reversal phase.

After completing the reversal phase of the VMAC task, participants completed the Alcohol Use Disorders Identification Test (AUDIT: Saunders, Aasland, Babor, De la Fuente, & Grant, 1993) to assess alcohol use risk. The AUDIT is a 10-item self-report measure developed by the World Health Organisation, with scores of 8 or more taken to indicate hazardous/risky alcohol consumption.

2.4. Data analysis

In all analyses reported below, 'high-reward' and 'low-reward' refer to the status of the distractors during the *training* phase (so that, for example, the distractor labelled high-reward in analyses signalled low reward during the reversal phase). Following previous protocols (Le Pelley et al., 2015), we discarded the first two trials after each break, along with timeouts (0.4% of all training trials and 0.6% of all reversal trials) and trials with RTs below 150 ms (0.9% of all training trials and 1.3% of all reversal trials). Analysis of RTs was restricted to correct responses only.

Since we were primarily interested in the effect on performance of transitioning from the reward phase to the unrewarded test phase, for the sake of comparability our main analyses relate to data from the VMAC task for the final trial-block of the training phase, and the single block of the reversal phase. Data across all blocks of the training phase are presented and analysed in Supplementary materials: the findings are consistent with those of analyses of the final training block.

We assessed the magnitude of the VMAC effect in each phase by comparing response time on trials with a high-reward versus a low-reward distractor (Supplementary materials report data from distractor-absent trials, which do not weigh on our critical hypotheses around effects of reward). In order to assess the critical question of whether the effect of reversal of reward-associations differed as a function of alcohol use, a negative binomial regression with log link function was run with AUDIT score as the dependent variable. Inspection confirmed that

AUDIT approximated a negative binomial distribution. The independent variables were: VMAC training score (given by RT for high-reward trials minus RT for low-reward trials during the training phase), VMAC reversal score (RT for trials with the previously-high-reward distractor minus RT for trials with the previously-low-reward distractor during the reversal phase), age, and gender. We controlled for age and gender due to research showing their influence on alcohol use and/or reward-driven attentional capture (Anderson, Faulkner, Rilee, Yantis, & Marvel, 2013; Roper, Vecera, & Vaidya, 2014). There was no evidence of multicollinearity in the regression model (all variance inflation factors < 2). A robust estimator covariance matrix and Pearson chi-square scale parameter method were used.[1]

In a follow-up analysis, we split participants into low-risk (AUDIT score below 8; $n = 90$) versus risky level drinkers (AUDIT score 8 or above; $n = 32$), and used independent sample *t*-tests to compare VMAC training score and VMAC reversal score between groups.

3. Results

Across all participants, median AUDIT score was 4 (range 0–22). Thirty-two participants scored 8 or above, indicating a risky level of drinking. Table 1 presents sample descriptive information by alcohol risk status.

Accuracy in the VMAC task was high during both the training and reversal phases, and did not differ significantly between high- and low-reward trials (Table 2; nor did this pattern differ as a function of alcohol use, see Supplementary materials for detailed analyses). As in previous work (Le Pelley et al., 2015), analyses therefore focussed on RT. Across participants, response time for high-value distractor trials was significantly greater than for low-value distractor trials during the training phase, $t(121) = 5.6$, $p < .001$, $d_z = 0.51$; see Table 2. That is, across all participants there was a clear VMAC effect during training – the reward manipulation produced an attentional bias, even though in the current study the points that participants earned merely unlocked medals rather than providing a monetary bonus. This confirms that the implementation of the task used in this study is sensitive to detecting effects of reward on attention. Across all participants, RTs for previously-high-reward and previously-low-reward trials did not differ significantly during the reversal phase, $t(121) = 0.64$, $p = .526$, $d_z = 0.06$.

Table 3 shows the results of the negative binomial regression on AUDIT scores. The regression model was significant overall ($LR\ \chi^2 = 12.1$, $p = .016$). Critically, VMAC reversal score was significantly associated with AUDIT score ($Wald\ \chi^2 = 9.9$, $p = .002$). Fig. 1b presents AUDIT scores as a function of VMAC reversal scores.

Fig. 1c shows VMAC training and reversal scores for participants reporting low-risk ($n = 90$) versus risky ($n = 32$) levels of alcohol use. The groups did not differ significantly in terms of VMAC score at the end of the training phase, $t(120) = 0.21$, $p = .836$, $d = 0.04$. During the reversal phase however, risky drinkers showed a significantly greater VMAC score (indicating persistence of the attentional bias formed during training) than low-risk drinkers, $t(120) = 2.70$, $p = .008$, $d = 0.56$. While the low-risk and risky alcohol-use groups differed noticeably in size, Levene's tests revealed that variance in VMAC scores of these groups was not significantly different during training (3890 vs 5448 ms, $F(1,121) = 0.34$, $p = .56$) or reversal (2928 vs 3193 ms, $F(1,121) = 0.34$, $p = .56$); consequently it is appropriate to compare group scores using *t*-tests (as we have done). That said, we note that the same pattern of significant findings emerges if we instead use Welch's t-tests (which do not assume equal variances), or a non-parametric Mann-Whitney test (which makes no distributional assumptions at all). In both cases there is no significant between-group difference in VMAC scores in training, $t(47.7) = 0.19$, $U(122) = 1397$, both $ps > .80$, but a significant difference during the reversal phase, $t(52.6) = 2.64$, $U(122) = 1024$, both $ps \leq .015$. The similar results across parametric and non-parametric analyses also suggest that findings were not a consequence of outlying data-points.

One-sample t-tests within each alcohol-use group revealed that for

Table 1
Descriptive statistics by alcohol risk status.

		Alcohol risk status	
		Low risk	Risky
Subsample size	n	90	32
	Females	62	18
Age	M	20.6	20.3
	SEM	0.2	0.3
VMAC training	M	32.4	35.2
	SEM	6.6	13.1
VMAC reversal	M	−4.8	25.7
	SEM	5.7	10.0
AUDIT score	Mdn	3	11
	Range	0–7	8–22

Note. 'VMAC' = value-modulated attentional capture score (in ms), given by the difference in response time on trials featuring a distractor that was paired with high reward during the training phase, and response time on trials featuring a distractor that was paired with low reward during the training phase. 'VMAC training' = VMAC score calculated over the final two trial-blocks of the initial training phase. 'VMAC reversal' = VMAC score calculated over the two trial-blocks of the reversal phase. 'AUDIT' = Alcohol Use Disorders Identification Test; score of 8 or above defines risky drinking.

Table 2
VMAC task data, averaged across all participants.

Phase			Distractor type		*t*	*p*
			High-reward	Low-reward		
Training	RT (ms)	M	662.5	629.3	5.6	< .001
		SEM	12.6	11.9		
	Accuracy (%)	M	90.1	90.7	1.5	.141
		SEM	0.6	0.6		
Reversal	RT (ms)	M	651.1	647.8	0.64	.53
		SEM	12.1	12.05		
	Accuracy (%)	M	90.9	90.1	0.9	.360
		SEM	0.9	0.8		

Note. t- and p-values are for paired samples *t*-tests (df = 121) comparing performance on trials with a high-reward versus a low-reward distractor.

Table 3
Results of negative binomial regression on AUDIT scores.

Factor	β	SE	Wald χ^2	*p*
Age	−0.03	0.04	0.63	.428
Gender	0.19	0.18	1.10	.294
VMAC training	0.00	0.00	0.05	.820
VMAC reversal	**0.01**	**0.00**	**9.89**	**.002**

Note. 'VMAC' = value-modulated attentional capture score (in ms), given by the difference in response time on trials featuring a distractor that was paired with high reward during the training phase, and response time on trials featuring a distractor that was paired with low reward during the training phase. 'VMAC training' = VMAC score calculated over the final two trial-blocks of the initial training phase. 'VMAC reversal' = VMAC score calculated over the two trial-blocks of the reversal phase. 'AUDIT' = Alcohol Use Disorders Identification Test. Significant results ($p < .05$) are shown in bold.

[1] Regression results were very robust: the critical finding of a relationship between VMAC reversal score and AUDIT score did not depend on the specific analytical approach used here. In Supplementary materials we demonstrate that the same finding emerges in analysis without covariates, in a linear regression, in a binary logistic regression (AUDIT risk), and in a linear regression where VMAC reversal score is the dependent variable and AUDIT score a predictor variable.

low-risk drinkers VMAC score was significantly greater than zero (high-reward > low-reward) during training, $t(89) = 4.93$, $p < .001$, $d_z = 0.52$, but did not differ significantly from zero during reversal, $t(89) = 0.83$, $p = .407$, $d_z = 0.09$. By contrast, risky drinkers showed a significant, positive VMAC score during both training, $t(31) = 2.70$, $p = .011$, $d_z = 0.48$, and reversal, $t(31) = 2.57$, $p = .015$, $d_z = 0.45$.

4. Discussion

The findings were consistent with our hypothesis: namely that alcohol use risk would be associated with inflexible reward-related attentional bias, and more specifically a deficit in reversal of the value-modulated attentional capture (VMAC) effect. Across all participants we observed a robust pattern wherein—during training—responses were slower (but no more accurate) on trials featuring a high-reward distractor than a low-reward distractor. That is, the high-reward colour was more likely to distract participants from their task of locating and responding to the target as rapidly as possible, consistent with the idea that the signal of high reward was more likely to capture participants' attention. The critical finding of our study is that participants differed in their response to a reversal of the colour–reward associations, as a function of their alcohol use risk: we observed this pattern in regression-based analyses treating AUDIT score as a continuous variable, and in group-based analyses of low-risk versus risky alcohol use groups. Low-risk participants showed a rapid change in behaviour: the trained bias towards the (previously) high-reward stimulus disappeared in the reversal phase, with a numerical (though non-significant) bias towards the previously-low-reward/now-high-reward distractor developing. Thus low-risk participants' behaviour showed signs of rapid adaptation to the prevailing reward relationships, which presumably would have solidified had we extended the reversal phase. By contrast, participants reporting risky alcohol use showed little sensitivity to the change in reward relationships: for these participants the attentional bias formed during training persisted through the reversal phase, despite instruction and experience of the reversed colour–reward contingencies.

Our findings are consistent with the idea that addiction-related behaviours are associated with differences in the extent to which reward-signals come to influence behaviour (Albertella et al., 2017; Anderson et al., 2013; Berridge et al., 2009). More specifically, our data demonstrate that risky alcohol use is associated with particularly persistent reward-related attentional biases that are inflexible in the face of experience of changed (reversed) stimulus–reward relationships. Unlike prior research that has focused on reversal learning of instrumental response behaviours in addiction (Fineberg et al., 2014; Gillan et al., 2016; Izquierdo & Jentsch, 2012), in the current study participants were not required to respond to the critical reward-related stimuli; indeed, they would perform better (earn more points) if they ignored the distractors entirely. Our findings therefore suggest that addiction-related behaviours are associated with deficits—specifically, with rigidity—in lower-level, more automatic processes of attentional processing and stimulus prioritisation.

The association between alcohol use and VMAC reversal deficits observed in the current study may be interpreted in several ways. First, it may be that exposure to risky levels of alcohol use causes functional impairment to brain areas implicated in reversal learning. One possible locus is the orbitofrontal cortex (OFC: Ragozzino, 2007) especially given evidence demonstrating frontal brain dysfunction in alcohol use disorders (for a review, see Moorman, 2018). More critical to showing direction of effect, a recent animal study found that chronic alcohol exposure in rats disrupts OFC-mediated top-down control over striatal areas and thereby promotes habitual responding (Renteria, Baltz, & Gremel, 2018). An alternative possible locus is the hippocampus, which is also implicated in reversal learning (Anacker & Hen, 2017) and compulsivity (Rao et al., 2018; Reess et al., 2018), and is known to undergo long-term changes following alcohol use. For instance, alcohol use in college students has been longitudinally associated with changes in the hippocampus (Meda et al., 2018). Also, exposure to alcohol in adolescence has been implicated in hippocampal dysfunction (McClain et al., 2011); this is notable with regard to the current study since those who drink at risky levels typically have an earlier age of first alcohol use (Grant & Dawson, 1997; Hingson, Heeren, & Winter, 2006).

Alternatively, the current findings may be interpreted as reflecting pre-existing individual differences in brain functioning in areas related to reversal learning or attentional flexibility, which contribute to the development and/or maintenance of risky alcohol use. Supporting this view, there is evidence that abnormalities in OFC structure or functioning are associated with alcohol and substance use prospectively (Cheetham et al., 2017), and genetic risk (Hill et al., 2009). Further, as mentioned earlier, researchers are beginning to recognise that compulsive disorders may be predated by risk markers related to compulsivity, such as cognitive inflexibility (Chamberlain et al., 2007). The current study supports this view and suggests further that such a predisposition towards rigidity may also be seen for addiction-related behaviours.

Another noteworthy finding of the current study is that VMAC during the training phase was not significantly associated with alcohol use risk, which might seem in contrast to previous research suggesting an association between propensity to addictive behaviours and the development of sign-tracking behaviour (Flagel et al., 2009). However, other research suggests that the relationship between attentional bias and substance use may be influenced by motivational state. For instance, Marhe et al. (2013) found that attentional bias for drug cues was significantly higher among patients who relapsed compared to those who maintained abstinence just before relapse occurred, suggesting that attentional bias does predict relapse, but only just before the relapse occurs. Thus, it might be the case that the initial development of VMAC (our analogue of sign-tracking) is influenced by current motivational factors and hence somewhat noisy, while reversal deficits are more reflective of a stable neurocognitive marker and so more easily detectable.

As noted in the Introduction, previous research has argued that AOD use is related to attentional bias towards stimuli associated with that substance (Field & Cox, 2008; Lubman et al., 2000; Nikolaou et al., 2013). Such studies have typically used variants of the *visual probe task*. On each trial, participants are presented with two pictures: one substance-related (e.g., a glass of beer) and one neutral (e.g., a soft drink). A target probe then appears in the location of one of the pictures, chosen randomly. Participants reporting high levels of AOD use are often found to be faster to respond to a target appearing in the location of the substance-related picture than the neutral picture, which is taken as evidence of a substance-related attentional bias. However, the visual probe task procedure has several limitations. First, the substance-related and neutral pictures differ systematically in terms of their visual properties, and potentially in their familiarity, valence etc. Second, there is no clear optimal strategy in this task: since the target is equally likely to appear in either location, it makes little difference to overall performance if participants choose to attend to the substance-related picture, the neutral picture, or remain at central fixation. Consequently, such studies are typically unable to distinguish between relatively automatic attentional bias elicited by the stimuli, versus endogenous, goal-directed attentional strategies (AOD users may prefer to look at substance-related pictures than neutral pictures, and may hence do so in a goal-directed way). Issues such as these may contribute to the somewhat unreliable nature of attentional biases revealed by studies using the visual probe task (Jones, Christiansen, & Field, 2018). By contrast, in the VMAC task used in the current study the high-reward and low-reward distractors were matched for their physical features, familiarity, valence etc. through counterbalancing of colour assignments across participants. Moreover, participants had a clear goal (respond to the diamond target as quickly as possible to earn reward). The finding of a reward-related attentional bias towards the distractors even when attending to these distractors was directly counterproductive

therefore suggests that this bias reflects the operation of relatively automatic processes. Most importantly, the fact that colour–reward associations were arbitrary in the current study (e.g., orange was established as a signal of high reward *in the context of the experiment*, in contrast to a picture of beer being a pre-existing and general signal of alcohol reward) meant we could reverse these associations and hence test the (in)flexibility of reward-related attentional biases; this manipulation could not easily be implemented in a standard visual probe task procedure with substance-related stimuli. Finally, the current study used stimuli related to monetary reward, rather than to AOD reward; this allows us to investigate whether AOD use is associated with a *general* difference in attentional bias that extends beyond specific effects of AOD substances to influence attention related to non-drug reward (Albertella et al., 2017; Albertella et al., 2019; Anderson et al., 2013). We encourage future research using the VMAC procedure in the context of AOD use in order to establish whether it provides a more reliable measure of (differences in) attentional bias than the visual probe task.

The setting of this study created certain limitations. First, we were unable to assess use of drugs other than alcohol; future studies may benefit from obtaining a more thorough collection of alcohol and other drug use data, which would enable statistical control for other drug use and age of first and/or risky use. It is also noteworthy that, overall, our sample drank at relatively low levels, and there were relatively few participants identified as risky drinkers based on AUDIT scores (n = 32). This could be seen as a strength of the study, since it suggests that abnormalities in reward-related attentional flexibility are related to addiction risk in a non-clinical sample; i.e., that cognitive markers are present even at low drinking levels. Nevertheless, it would also clearly be valuable to establish whether these findings generalise to clinical populations of heavy drinkers (with status confirmed using DSM criteria; APA, 2013), as well as other compulsive behaviours. Second, time limitations meant that the reversal phase of the current study was relatively brief. This short reversal phase was sufficient and appropriate for the research question addressed here—investigating the immediate effect on performance of a reversal in stimulus–reward contingencies. However, it would be interesting to track further any changes in attentional bias over an extended reversal phase. Finally, a measure of response inhibition or cognitive control may have helped to separate contributions of cognitive control deficits to those of reversal learning. However, it is likely that the current VMAC-reversal task worked so well as a marker of AUDIT risk as it offered a context in which cognitive control, reward learning, and cognitive flexibility could interact functionally. Assessing these cognitive functions independently of each other would not be as informative as assessing their interactive output, the latter being what drives real-world behaviour. Lastly, the current study is limited by the classroom setting in which it took place. Participants were potentially in view of others, which raises the concern that they may not have answered truthfully about drinking. However, while this could add noise to the data, it is hard to see how any classroom-based confound could have systematically driven the results seen here. Hence, we feel that the significance of our findings points to either a very robust effect that can be seen despite classroom-related limitations, or that such limitations did not in fact pose a critical issue.

In conclusion, VMAC-reversal is a promising adaptation of the original task and appears sensitive to addiction risk. Future studies are needed to explore this in clinical groups, and potentially behavioural addictions and compulsive disorders. Given the strong link between reversal learning deficits and compulsive disorders in general (Izquierdo & Jentsch, 2012; Robbins, Gillan, Smith, de Wit, & Ersche, 2012), VMAC-reversal might be a useful measure to use alongside traditional reversal learning paradigms to better understand the components of cognitive rigidity and their relationship with compulsivity across behavioural domains.

Declaration of Competing Interest

None to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.abrep.2019.100195.

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