Association of the OPRM1 A118G polymorphism and Pavlovian-to-instrumental transfer: Clinical relevance for alcohol dependence

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Abstract

Background: Pavlovian-to-instrumental transfer (PIT) quantifies the extent to which a stimulus that has been associated with reward or punishment alters operant behaviour. In alcohol dependence (AD), the PIT effect serves as a paradigmatic model of cue-induced relapse. Preclinical studies have suggested a critical role of the opioid system in modulating Pavlovian–instrumental interactions. The A118G polymorphism of the OPRM1 gene affects opioid receptor availability and function. Furthermore, this polymorphism interacts with cue-induced approach behaviour and is a potential biomarker for pharmacological treatment response in AD. In this study, we tested whether the OPRM1 polymorphism is associated with the PIT effect and relapse in AD.

Methods: Using a PIT task, we examined three independent samples: young healthy subjects (N = 161), detoxified alcohol-dependent patients (N = 186) and age-matched healthy controls (N = 105). We used data from a larger study designed to assess the role of learning mechanisms in the development and maintenance of AD. Subjects were genotyped for the A118G (rs1799971) polymorphism of the OPRM1 gene. Relapse was assessed after three months.

Results: In all three samples, participants with the minor OPRM1 G-Allele (G+ carriers) showed increased expression of the PIT effect in the absence of learning differences. Relapse was not associated with the OPRM1 polymorphism. Instead, G+ carriers displaying increased PIT effects were particularly prone to relapse.

Conclusion: These results support a role for the opioid system in incentive salience motivation. Furthermore, they inform a mechanistic model of aberrant salience processing and are in line with the pharmacological potential of opioid receptor targets in the treatment of AD.

Keywords

Alcohol dependence, learning, decision making, OPRM1 A118G, opioid system

Introduction

Contextual stimuli are important modulators in the way we learn and can promote specific behaviours. One mechanism underlying contextual learning is the so-called Pavlovian-to-instrumental transfer (PIT). The PIT effect capture the influence of Pavlovian conditioned stimuli (CSs) on instrumental behaviour, with appetitive Pavlovian stimuli specifically promoting approach and reducing withdrawal, and aversive Pavlovian stimuli promoting withdrawal and reducing approach (Huys et al., 2011), thus reflecting a powerful mechanism affecting behavioural choices across humans (Talmi et al., 2008) and animals (Dickinson et al., 2000; O’Connor et al., 2010). Moreover, the PIT effect has been used as a quantification of incentive salience attribution, that is, the extent to which formerly neutral cues become attractive, themselves desired, and therefore ‘wanted’ (Huys et al., 2014; Meyer et al., 2012).

Crucially, incentive salience attribution is one prominent mechanism underlying several disorders of compulsivity, such as alcohol dependence (AD; Corbit and Janak, 2007) and other addictive disorders (LeBlanc et al., 2012). Also, interindividual differences in PIT have been associated with addiction vulnerability and maintenance. For instance, preclinical work suggests an association between the magnitude of PIT and addictive behaviour, such as compulsive alcohol drinking (Barker et al., 2012; Corbit and Janak, 2007). Preclinical studies have also consistently reported that non-drug-related (e.g. food or sucrose reward) CSs lead to increased...
responding during PIT in addicted animals (LeBlanc et al., 2013; Oslund et al., 2014; Saddoris et al., 2011). Moreover, we have recently shown that the PIT effect in humans serves as a vulnerability marker for the development and maintenance of AD (Garbusow et al., 2014, 2019; Schad et al., 2019a; but see van Timmeren et al., 2020). The behavioural and neural correlates of PIT have been associated with relapse in AD (Garbusow et al., 2016; Sekutowicz et al., 2019; Sommer et al., 2020) and were predictive of future drinking behaviour in adolescents (Sekutowicz et al., 2019).

Although contemporary theories emphasise the involvement of the dopaminergic system in incentive salience, recent findings suggest the opioid system as another important player (Pecina and Berridge, 2013; van Steenbergen et al., 2019). The opioid system has been primarily linked to hedonic features of a reward, also termed ‘liking’ as opposed to ‘wanting’, which reflects the motivational properties to promote a certain behaviour rather than its hedonic value. However, preclinical studies have shown that stimulation of the μ-opioid (MOP) system in the nucleus accumbens directly enhances incentive motivation (or ‘wanting’) for reward (Pecina and Berridge, 2013). In animals, experimental manipulation of the opioid system can mediate the influence of reward-guided and stimulus-guided decisions on choice (Laurent et al., 2012), increase motivation for different reward types (Mahler and Berridge, 2012) and mediate the motivating influence of cue-triggered reward expectations (Lichtenberg and Wassum, 2017). In humans, evidence for a functional role of the opioid system in mediating ‘wanting’ mainly stems from pharmacological challenges. For instance, MOP agonists and antagonists selectively enhance and decrease processing efficiency in a reward task (Eikemo et al., 2017) and increase and decrease the motivation to view positive valenced stimuli, respectively (Chelnokova et al., 2014). Likewise, opioid receptor antagonists reduced physical effort produced to obtain reward and increased negative facial reactions during reward anticipation (Korb et al., 2019).

In humans, the role of the opioid system in mediating the PIT effect as one further quantification of incentive salience (or ‘wanting’) is less clear. The opioid receptor antagonist naltrexone could decrease alcohol cue-induced activation of the ventral striatum (Myrick et al., 2008) and cue-induced impulsive responding (Mitchell et al., 2007). However, to date, there are only two studies investigating the role of the opioid system in mediating human PIT-like effects (Weber et al., 2016; Wiers et al., 2009), reporting reduced PIT after blockade of the MOP receptor (naltrexone) in healthy humans (Weber et al., 2016) and increased automatic approach tendencies in G+ carriers of the OPRM1 polymorphism to alcohol-associated stimuli (Wiers et al., 2009). The overarching aim of our study was to further elucidate the role of the human opioid system in mediating the PIT effect in both healthy subjects and those with AD.

A common mechanism of quantifying interindividual differences in the human opioid system is the determination of the MOP receptor single nucleotide polymorphism (OPRM1). The OPRM1 gene codes for the MOP receptor, an inhibitory G-protein coupled receptor that binds endogenous opioid peptides such as β-endorphin and enkephalins as well as exogenous opioids such as morphine and heroin (Burns et al., 2019; Kieffer and Gaveriaux-Ruff, 2002). Opioid receptors are distributed widely in the human brain and modulate brain function at all levels of neural integration, including the mesolimbic system as part of the brain’s reward pathway.

Human studies investigating the OPRM1 polymorphism have suggested a crucial role of this single nucleotide polymorphism (SNP) in AD, treatment response and automatic approach biases to conditioned cues (Chamorro et al., 2012; Filbey et al., 2008; Ray and Hutchison, 2004; Wiers et al., 2009). The A118G (rs1799971) polymorphism of the OPRM1 gene alters the function of MOP receptors, such that the G variant binds beta-endorphin three times more strongly than the A variant, potentially also affecting receptor availability (Heinz et al., 2005). We henceforth refer to the minor OPRM1 G-allele carriers as G+ carriers. G+ carriers were shown to report higher subjective alcohol-associated feelings of intoxication (Ray and Hutchison, 2004) and craving (Van Den Wildenberg et al., 2007) and have a higher risk for positive family history (Ray and Hutchison, 2004). However, conflicting results stem from large genome-wide association studies (GWAS) and candidate gene studies (Kong et al., 2017), which could not replicate an association between AD and OPRM1 genotype, corresponding with a recent report on converging evidence against an association between the OPRM1 A118G polymorphism and alcohol consumption and sedation (Sloan et al., 2018).

The analyses presented here aimed to answer three questions. (1) Is the OPRM1 polymorphism associated with the PIT effect across three independent cohorts? (2) Is the association between the PIT effect and the OPRM1 polymorphism different in patients with AD compared to healthy controls (HCs)? (3) Is the association between the PIT effect and the OPRM1 polymorphism relevant for treatment outcome in the way that it is different in prospectively relapsing and abstinent patients with AD?

Methods

Subjects

All subjects were recruited between 2012 and 2018 as part of a larger study (LeAD study, ClinicalTrials.gov identifiers: NCT01744834, NCT01679145 and NCT02615977) investigating behavioural, genetic and neuroimaging alterations associated with reward-based learning as (a) predictors for the development of AD in a sample of young 18-year-old male subjects recruited from the national registry and (b) the maintenance of AD with respect to relapse and drinking behaviour in a sample of patients suffering from AD and an age, education and sex-matched HC sample (for previously published results of our sample, see, amongst others, Garbusow et al., 2014, 2016, 2019). Thus, this study comprised two independent HC samples that significantly differed with regards to several sociodemographic variables (see Supplemental Table S2 for between-group differences). As previous analyses (Sebold et al., 2016) indicated substantial differences in PIT effects between these cohorts, we did not merge both control samples but instead analysed the influence of the OPRM1 polymorphism on the PIT effect separately in these two control cohorts (analysis 1).

The assessed samples were a subsample of the three cohorts mentioned above for which genetic data were available: 18-year-old male subjects (N=161, henceforth referred to as young controls), recently detoxified patients with AD (N=186) and age-matched HCs (N=105, henceforth referred to as middle-aged controls). For a precise overview of the selection procedures, see Supplemental Information 1 and Supplemental Figure S1.
For a complete description of exclusion criteria, see Garbusow et al. (2016). Briefly, all subjects were free from psychotropic medication, had no history of substance dependence (DSM-IV, except from AD in the AD group) or current substance use (DSM-IV, except for nicotine use), no other current DSM-IV axis I psychiatric or neurological disorders and no borderline personality disorder as assessed by the computer-based Composite International Diagnostic Interview (Jacobi et al., 2013; Wittchen, 1997). Participants’ demographic and clinical characteristics are outlined in Table 1. Participants gave written informed consent before study inclusion. The study was approved by the local ethics committees of the Technical University of Dresden and Charité Universitätsmedizin Berlin.

To define relapse across patients with AD, a three-month follow-up was performed using the Time Line Follow Back procedure (Sobell and Sobell, 1992). Relapse was defined as at least five standard drinks (e.g. one standard drink = 0.33 L beer) on one occasion for male participants and at least four standard drinks for female participants according to the World Health Organization (WHO; 2014) definition of high-risk consumption. A total of 51 patients were classified as relapers (of whom 37 were G− and 14 were G+ carriers), whereas 94 patients were classified as abstainers (of whom 78 were G− and 16 were G+ carriers). The remaining 41 patients could not be contacted during the follow-up period.

**Task**

We used a PIT task as previously described (Garbusow et al., 2014, 2016; Sommer et al., 2017). The task consisted of four phases (of which the first three phases are depicted in Figure 1): (a) instrumental learning, (b) Pavlovian learning, (c) PIT and (d) forced choice task followed by a rating scale of the stimuli.

**Instrumental learning.** Subjects had to learn to collect ‘Go’ shells and leave ‘No-Go’ shells by repeatedly pressing a button while receiving probabilistic feedback. In order to collect a shell, subjects had to move a red dot onto the selected shell by repeated button presses within two seconds. We instructed the subjects to maximise their profit. For this, they should use the probabilistic feedback to find out via trial and error what is a ‘good shell’, which in ‘most cases’ lead to wins when collected, and leave ‘bad shells’, which in ‘most cases’ lead to wins when not collected. Each button press moved the red dot a fraction of the way towards the shell. To collect a ‘Go’ shell correctly, subjects had to press the button five or more times, and to leave a ‘No-Go’ shell, subjects had to press the button three times.

**Pavlovian learning.** Pavlovian learning consisted of 80 trials in which compound visual and auditory stimuli (CS) were predictive of distinct monetary rewards or punishments (unconditioned stimulus (US); Figure 1.2). Each trial began with a three-second presentation of a compound CS (fractal picture and tone) which was then followed by a three-second presentation of two fixation crosses (on the left and right side of the screen). Then, the US (monetary reward or punishment) was presented for three seconds on the side where the CS had not been presented. Subjects were instructed to view the CS–US pairings passively and to memorise these associations. The set of CS consisted of six stimuli of which each was paired with positive (+2€/+1€), neutral (0€) or negative (−1€/−2€) outcomes, henceforth referred to as ‘money CS’.

**PIT phase.** Subjects performed 162 trials of the instrumental task again, this time without outcome feedback. Subjects were instructed that their choices still counted towards the final monetary outcome (so-called nominal extinction). The instrumental stimuli superimposed one of the money CSs presented during Pavlovian training (Figure 1.3), or one of four beverage stimuli (results not presented here, but see (Schad et al., 2019a; Sekutowicz et al., 2019; Sommer et al., 2017, 2020). Each instrumental stimulus (three ‘Go’ shells and three ‘No-Go’ shells) was combined with each money CS (fractal stimulus previously associated with either of −2€, −1€, 0€, +1€, +2€) for three times, resulting in 90 trials, which were of primary interest for this study. Each trial lasted 3.6 seconds.

**Forced-choice task.** This part of the task aimed to verify the acquisition of Pavlovian learning. In each trial, subjects had to choose between two sequentially presented compound money CSs from the Pavlovian training, each presented for two seconds. All possible compound CS pairings were presented three times in an interleaved randomised order.

**Pleasantness ratings.** After the task, subjects were asked to rate the pleasantness of the CSs (fractals and shells) from the Pavlovian learning phase and the instrumental learning phase on a Likert scale from 1 to 7 on the screen.

**Genotyping**

To genotype our sample, DNA was extracted semi-automatically with a Chemagen Magnetic Separation Module (PerkinElmer, Waltham, MA) from whole blood. All samples were genotyped with the Illumina Infinium Psych Array Bead Chip (Illumina, San Diego, CA). We assessed rs1799971, a SNP that is an A-to-G substitution (A118G), resulting in a functional amino acid substitution (Asn40Asp; Hartwell et al., 2020).

Because of the limited sample size, G-allele carriers (AG and GG) were grouped together. This approach is in keeping with precedent in the field (Persson et al., 2019; Way et al., 2009).

**Behavioural analyses**

Data were analysed using the R programming language (R Foundation for Statistical Computing, Vienna, Austria). Demographic, clinical and neuropsychological comparisons between G+ and G− OPRM1 carriers were examined using chi-square and t-tests (Table 1).
Table 1. Demographic, clinical and neuropsychological characteristics for all cohorts: young controls, middle-aged controls and patients with AD, split by OPRM1 polymorphism.

| Cohort                  | Alcohol-dependent patients (N = 186) | Middle-aged controls (N=105) | Young controls (N=161) |
|-------------------------|--------------------------------------|------------------------------|------------------------|
|                         | M (SD) | M (SD) | M (SD) | M (SD) | M (SD) | M (SD) | M (SD) | M (SD) | M (SD) | M (SD) | M (SD) | M (SD) |
| OPRM1                   |        |        |        |        |        |        |        |        |        |        |        |        |        |
| G− (N = 154)            |        |        |        |        |        |        |        |        |        |        |        |        |        |
| G+ (N = 32)             |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Test statistics         |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Age                     | 46.17 (10.49) | 47.09 (11.03) | t=−0.42, p=0.67 | 43.64 (11.1) | 46.04 (10.5) | t=−0.99, p=0.33 | 18.36 (0.2) | 18.37 (0.2) | t=−0.33, p=0.74 |
| Sex ( % male)           | 84%    | 81%    | χ²=0.2, p=0.67 | 83%    | 81%    | χ²=0.11, p=0.75 | 100% | 100% | NA |
| Years of education      | 14.97 (4.07) | 14.29 (2.52) | t=1.3, p=0.22 | 15.98 (3.22) | 15.37 (3.32) | t=0.79, p=0.43 | 11.7 (0.75) | 11.51 (1.34) | t=0.85, p=0.4 |
| Anxietya                | 4.37 (3.41) | 4.8 (3.37) | t=−0.63, p=0.53 | 2.32 (2.04) | 1.88 (2.21) | t=0.89, p=0.38 | 2.31 (2.19) | 2.92 (2.89) | t=−1.2, p=0.23 |
| Depressionb              | 3.5 (3.7) | 4.33 (3.33) | t=−1.23, p=0.23 | 1.48 (1.98) | 1.85 (2.62) | t=−0.65, p=0.52 | 1.67 (1.75) | 1.8 (2) | t=−0.39, p=0.7 |
| Cravingc                | 12.76 (7.94) | 12.52 (8.57) | t=0.14, p=0.88 | 2.4 (2.41) | 3.68 (4.03) | t=−1.31, p=0.2 | 3.47 (3.01) | 4.65 (3.48) | t=−1.91, p=0.7 |
| Impulsivityd             | 31.63 (6.67) | 31.84 (5.57) | t=−0.19, p=0.85 | 29.32 (5.4) | 28.84 (5.3) | t=0.39, p=0.69 | 29.99 (5.15) | 31.82 (4.56) | t=−2.13, p=0.04 |
| Cognitive speede        | 9.27 (2.76) | 9.48 (2.78) | t=−0.39, p=0.7 | 10.58 (2.82) | 10.92 (3.78) | t=−0.42, p=0.68 | 11.5 (2.2) | 11 (2.59) | t=1.11, p=0.27 |
| Working memoryf         | 6.5 (1.93) | 6.77 (1.61) | t=−0.82, p=0.41 | 7.41 (1.95) | 7.62 (2.43) | t=−0.40, p=0.69 | 8.04 (1.95) | 8.02 (2.21) | t=0.04, p=0.96 |

The variables were assessed by means of *the anxiety and depression subscales of the Hospital Depression and Anxiety Questionnaire; †the obsessive compulsive drinking scale, ‡the Barratt Impulsiveness Scale and the following subtest of the Wechsler Intelligence Test: §the digit symbol substitution test and ¶the digit span backwards test.

AD: alcohol dependence.
Analysis of the PIT phase was of primary interest, but we analysed all other phases as well (see Supplemental Information 6, Supplemental Information 7, Supplemental Information 8 and Supplemental Information 10). In the PIT phase, the PIT effect reflects the interaction between the valence of the background stimulus and the accuracy of the foreground instrumental action. We were specifically interested whether the OPRM1 genotype covaried with PIT effect, that is, the way that positive and negative stimuli influence ‘Go’ and ‘No-Go’ actions. More precisely, we asked whether the genetic phenotype would interact with the extent to which a positive stimulus facilitates ‘Go’ responses but impairs ‘No-Go’ responses and, vice versa, a negative stimulus facilitates ‘No-Go’ responses but impairs ‘Go’ responses.

As outlined in the introduction, the analyses presented here aimed to elucidate: (a) the association between the OPRM1 polymorphism and the PIT effect, (b) the clinical relevance of this association for AD and (c) the relevance of this association for treatment outcome. Across these different analyses, we coded a participant’s accuracy of the PIT phase as correct (1) if a ‘Go’ shell was collected or a ‘No-Go’ shell was left, and as false (0) if a ‘No-Go’ shell was collected or a ‘Go’ shell was left. We used a binomial mixed effect regression as implemented in the lme4 package (Bates et al., 2015). We regressed the participant’s accuracy (correct or incorrect) on Pavlovian valence (negative, neutral or positive, dummy coded with neutral as the reference), instrumental action (‘Go’ or ‘No-Go’, coded as 0.5 and −0.5) and OPRM1 polymorphism (G− or G+, coded as −0.5 and +0.5) and tested for interaction between these factors. Subjects were added as random effects (random intercept model). We performed model comparisons to ensure that this model was the best-fitting model across subjects (see Supplemental Information 2).

**Analysis 1: Association between the PIT effect and the OPRM1 polymorphism across cohorts.** To test whether the OPRM1 polymorphism was associated with the PIT effect in all three cohorts, we performed the above-described analysis for all three cohorts separately (Supplemental Figure S1).

**Analysis 2: Alcohol-related group differences for the association between the PIT effect and the OPRM1 polymorphism.** To test whether the interaction between the PIT effect and the OPRM1 polymorphism was significantly different between HCs and patients with AD, we performed the above-described regression model (see analysis 1) but additionally added group (HC or AD, coded as 0.5 and −0.5) as an additional fixed effect and allowed interaction with all predictors (Supplemental Figure S1). For this analysis, we only included patients with AD and middle-aged control subjects (who were initially sampled as a comparison group of patients with AD). Both groups profoundly differed across several socio-economic and clinical variables (Supplemental Table S2). Increased depression, anxiety, craving and impulsivity as well as reduced cognitive speed and working memory are features instead of confounders of AD. Thus, as suggested by Miller and Chapman (2001), we did not control for these variables. Years of education was the only variable we added as a covariate because groups significantly differed in these variables despite our efforts of matching.
Table 2. Results of analysis 1. Effects of the regression analysis from the PIT part for all three cohorts.

| Group                                | Alcohol-dependent patients (N=186) | Middle-aged controls (N=105) | Young controls (N=161) |
|--------------------------------------|-----------------------------------|-----------------------------|------------------------|
|                                      | $\chi^2$ | p-Value | $\chi^2$ | p-Value | $\chi^2$ | p-Value |
| Pavlovian CS valence                 | 11.723  | 0.003   | 5.599   | 0.061   | 15.105  | 0.001   |
| Instrumental behavior                | 7.057   | 0.008   | 13.108  | 0.0003  | 0.159   | 0.690   |
| OPRM1 polymorphism                   | 0.002   | 0.963   | 0.046   | 0.831   | 0       | 0.994   |
| Pavlovian valence × Instrumental behavior | 2074.63 | <0.0001 | 912.67  | <0.0001 | 365.68  | <0.0001 |
| Pavlovian valence × OPRM1 polymorphism | 0.224  | 0.894   | 0.074   | 0.964   | 0.629   | 0.730   |
| Instrumental behavior × OPRM1 polymorphism | 13.917 | 0.0002  | 18.930  | <0.0001 | 7.757   | 0.005   |
| Pavlovian valence × instrumental behavior × OPRM1 polymorphism | 12.723 | 0.002   | 9.027   | 0.011   | 20.691  | <0.0001 |

All interaction effects with the OPRM1 polymorphism in the young control cohort remained significant after controlling for self-reports of impulsivity, which was significantly different between G+ and G− carriers in this cohort (see Table 1); Statistically significant values are shown in bold.

PIT: Pavlovian-to-instrumental transfer; CS: conditioned stimulus.

Analysis 3: Relapse-related group differences for the association between the PIT effect and the OPRM1 polymorphism. To test whether the interaction between the OPRM1 polymorphism and the PIT effect was significantly different between patients with AD who relapsed and those who remained abstinent, we performed the above described regression analysis (see analysis 1) but added relapse (relapsers or abstainers, coded as 0.5 and –0.5) as an additional fixed factor and allowed interaction with all predictors. For this analysis, we only included patients with AD for whom relapse data were available (n=145; Supplemental Figure S1). Relapsing patients did not differ from abstaining patients in any demographic or clinical variables, except for craving (where relapsing patients had significantly higher OCDS scores (Anton et al., 1995; Mann and Ackermann, 2000) than abstaining patients ($t=−2.66, p=0.01$). Thus, we added craving as a covariate of no interest in this analysis.

Post hoc analyses

For analyses 2 and 3, we were particularly interested in how the PIT effect was modulated by the OPRM1 polymorphism and whether this depended on group, respectively. Thus, in our post hoc analyses, we focused on these contrasts (analysis 2: G+ vs. G− carriers/HCs vs. ADs; analysis 3: G+ vs. G− carriers/relapsers vs. abstainers) and considered effects as significant when they survived Bonferroni correction for four comparisons ($p<0.01$). We found no evidence for a functional association between the OPRM1 polymorphism and AD. Descriptively, there were proportionally more G+ carriers among the HCs compared to the AD group – from the literature we would have expected the reverse results – although this difference was formally not statistically significant ($\chi^2_{(df=1)}=3.62, p=0.06$). Also, we found no evidence for a functional association between the OPRM1 polymorphism and relapse ($\chi^2_{(df=1)}=1.60, p=0.21$).

Behavioural data

Analysis 1: Association between the PIT effect and the OPRM1 polymorphism across cohorts. The first aim of this study was to test whether the OPRM1 polymorphism influences the PIT effect across three independent cohorts. In all three cohorts we found a significant PIT effect, that is, the interaction between Pavlovian valence (negative, neutral or positive) and instrumental action (‘Go’ or ‘No-Go’; Table 2), indicating that positive stimuli facilitated ‘Go’ responses but impaired ‘No-Go’ responses, whereas negative stimuli facilitated ‘No-Go’ responses but impaired ‘Go’ responses.

In all groups, respectively, we found no interaction between Pavlovian valence and OPRM1 polymorphism. However, the OPRM1 polymorphism interacted with instrumental action (Table 2). Crucially, we found a three-way interaction between Pavlovian valence, instrumental action and OPRM1 polymorphism in all cohorts. This result suggests that the OPRM1 polymorphism strongly interacts with the PIT effect in all three independent cohorts. In fact the PIT effect was significantly higher in G+ carriers compared to G− carriers (Figure 2 and Table 2).

To rule out that our PIT-related OPRM1 effect was simply due to the fact that G+ carriers showed stronger cue-induced modulation of liking, we further performed analyses of the rating data of the Pavlovian stimuli (pleasantness ratings; Supplemental Information 10). To this end, we first tested whether the OPRM1 polymorphism was associated with ratings of the stimuli, depending on the Pavlovian valence. In all cohorts, the OPRM1 polymorphism did not interact with Pavlovian valence (Supplemental Information 10). Moreover, adding the rating data as an additional covariate in our PIT analyses, all interaction between the

Results

Genotyping

Genotyping resulted in 353 participants homozygous for the major A allele, 89 participants with the AG combination and 10 participants homozygous for the G allele. OPRM1 genotype distribution did not significantly differ from Hardy–Weinberg equilibrium ($\chi^2_{(df=1)}=2.31, p=0.13$).

Demographic, clinical and neuropsychological comparisons between G+ and G− carriers in all three cohorts indicated no group differences (Table 1), except from increased self-reports of impulsivity assessed via BIS-15 (Meule, 2011) in G+ carriers compared to G− carriers in young healthy adults. Moreover, we
OPRM1 polymorphism, Pavlovian valence and instrumental action remained significant (patients with AD: \( p = 0.0004 \); middle-aged controls: \( p = 0.006 \); young controls: \( p < 0.0001 \)).

**Analysis 2: Alcohol-related group differences for the association between the PIT effect and the OPRM1 polymorphism.** The second aim of this study was to test whether the interaction between the PIT effect and OPRM1 polymorphism was significantly different between patients with AD and HCs. This analysis indicated a three-way interaction between Pavlovian valence, instrumental action and group and also a three-way interaction between Pavlovian valence, instrumental action and OPRM1 polymorphism. Thus, AD and the OPRM1 polymorphism were significantly and independently associated with the strength of the PIT effect per se (see Figure 2). Moreover, we found a three-way interaction between instrumental action, group and OPRM1 polymorphism. However, the four-way interaction between Pavlovian valence, instrumental action, group and OPRM1 polymorphism was not statistically significant (Table 3). Thus, the interaction between the PIT effect and the OPRM1 polymorphism was not statistically different between patients with AD and matched control subjects (Figure 2).

**Table 3.** Results of analysis 2. Effects of the regression analysis from the PIT part where we tested whether the interaction between the PIT effect and the OPRM1 polymorphism was significantly different between patients with AD and HCs.

|                     | \( \chi^2 \) | \( p \)-Value |
|---------------------|-------------|--------------|
| Pavlovian valence   | 13.183      | 0.001        |
| Instrumental action | 18.391      | <0.0001      |
| OPRM1 polymorphism  | 0.007       | 0.933        |
| Group               | 2.316       | 0.128        |
| Years of education  | 7.651       | 0.006        |
| Pavlovian valence × instrumental action | 2888.726 | <0.0001      |
| Pavlovian valence × OPRM1 polymorphism | 0.031 | 0.984        |
| Instrumental action × OPRM1 polymorphism | 0.374 | 0.540        |
| Pavlovian valence × group | 3.661 | 0.160        |
| Instrumental action × group | 4.187 | 0.041        |
| OPRM1 polymorphism × group | 0.015 | 0.901        |
| Pavlovian valence × instrumental action × OPRM1 polymorphism | 16.909 | <0.0001      |
| Pavlovian valence × instrumental action × group | 22.695 | <0.0001      |
| Pavlovian valence × OPRM1 polymorphism × group | 0.257 | 0.880        |
| Instrumental action × OPRM1 polymorphism × group | 30.727 | <0.0001      |
| Pavlovian valence × instrumental action × OPRM1 polymorphism × group | 0.318 | 0.853        |

HC: healthy control.
Analysis 3: Relapse-related group differences for the association between the PIT effect and the OPRM1 polymorphism. Last, we tested whether the observed interaction between the PIT effect and the OPRM1 polymorphism was associated with relapse. Again, we found a three-way interaction between the OPRM1 polymorphism, Pavlovian valence and instrumental action (Table 4). In addition, we observed an interaction between relapse status and instrumental action, and a three-way interaction between Pavlovian valence, instrumental action and relapse. This interaction was further modulated by the OPRM1 polymorphism, resulting in the expected four-way interaction between Pavlovian valence, instrumental action, OPRM1 polymorphism and relapse status (Figure 3 and Table 4). Thus, the interaction between the OPRM1 polymorphism and the PIT effect was statistically different between patients with AD who prospectively relapsed and those who remained abstinent. Post hoc tests indicated that the interaction between Pavlovian valence, instrumental action and the OPRM1 polymorphism was only significant for relapers ($p < 0.0001$) but not for abstainers ($p = 0.328$). Moreover, the interaction between Pavlovian valence, instrumental action and relapse was significant for G+ carriers ($p < 0.0001$) but not for G− carriers ($p = 0.09$).

**Discussion**

To explore and further understand the behavioural and genetic underpinnings of ‘wanting’ as an expression of incentive salience attribution in humans and to bridge the gap to preclinical results, we investigated the association between the OPRM1 polymorphism, PIT effect and relapse across a large cohort of patients with AD and two independent cohorts of HCs.
We demonstrate that (a) in all three independent cohorts, G+ carriers showed an increased PIT effect; (b) there is no difference between patients with AD and HCs in the interaction between OPRM1 and PIT; but (c) when merely investigating AD, relapsing patients carrying the G+ allele showed an increased PIT effect as opposed to abstaining patients, who did not show an association between OPRM1 genotype and PIT. We henceforth discuss these three main results.

**Analysis 1: Association between the PIT effect and the OPRM1 polymorphism across cohorts**

The first analysis demonstrated a clear association between the OPRM1 genotype and PIT in three independent human cohorts. Two studies have previously investigated the role of the human opioid system in PIT-like effects in healthy human subjects. Using a pharmacological challenge, Weber et al. (2016) demonstrated that naltrexone reduces PIT effects for primary reinforcers (e.g. food rewards). We here demonstrate that the opioid system is also involved in modulating PIT effects for secondary reinforcers (e.g. monetary rewards). Beyond this, the experimental design from Weber et al. (2016) also differed in several other aspects from our study. Weber et al. (2016) focused on the positive ‘limb’ of the PIT effect (the extent to which positive stimuli affect responses), whereas our paradigm also enabled us to examine the negative ‘limb’ of the PIT effect (the extent to which negative stimuli affect responses). Moreover, our instrumental task included both ‘Go’ and ‘No-Go’ responses, whereas the instrumental task by Weber et al. (2016) merely included a ‘Go’ component. Thus, in line with previous investigations (Guitart-Masip et al., 2011, 2014; Swart et al., 2017), our experimental manipulation enabled us to test for more complex valence–action interactions. These previous tasks in line with our results have identified a potentially phylogenetically induced bias for congruent action–valence responses (e.g. better performance when a ‘Go’ response was acquired to win) compared to incongruent action valence (e.g. when a ‘No-Go’ response was acquired to win).

A second study published by Wiers et al. (2009) investigated automatic appetitive action tendencies in male heavy-drinking carriers of the OPRM1 G allele. Heavy-drinking G+ carriers showed increased automatic approach tendencies not only to alcohol-associated stimuli but also to other appetitive stimuli (Wiers et al., 2009). This is in line with our finding of increased behavioural modulation in the presence of appetitive cues in AD G+ carriers. However, Wiers et al. did not include a control group in their study design and only included male sex, which limits generalisability and comparability to our results.

In summary, our data support the notion that the OPRM1 polymorphism serves as one biological agent associated with human PIT effect in both AD patients and HCs.

**Analysis 2: Alcohol-related group differences for the association between the PIT effect and the OPRM1 polymorphism**

We did not find a significantly different association between the PIT effect and the OPRM1 polymorphism between patients with AD and HCs, which partly reflects the ongoing debate and contradictory results published so far on the association between the OPRM1 genotype and AD (Hendershot et al., 2016; Kong et al., 2017; Ray and Hutchison, 2004; Sloan et al., 2018). Instead, we found that AD and the OPRM1 polymorphism are independent factors that both increase the PIT effect. Moreover, we found an interaction between instrumental action, OPRM1 polymorphism and group, indicating that the opioid system differently affects instrumental responses in AD patients and HCs. Exploratory post hoc analyses (Supplementary Information 4) indicated that AD G+ carriers showed increased ‘Go’ responses compared to ‘No-Go’ responses, whereas HC G+ carriers showed increased ‘No-Go’ responses compared to ‘Go’ responses. Of note, a positive PIT effect is accompanied by an overall increase of ‘Go’ responses, while a negative PIT effect is accompanied by an overall increase in ‘No-Go’ responding. Thus, the OPRM1 polymorphism may influence the positive PIT effect in patients with AD and the negative PIT effect in HC. A core feature of AD is the persistent substance consumption despite the negative consequences of consumption (Stacy and Wiers, 2010). We speculate that this paradox might partly be explained by an increased responsiveness of patients with AD to positively conditioned cues, which is stronger in G+ carriers. On the other hand, an increased responsiveness to negative stimuli might reveal a protective mechanism of healthy G+ carriers (S3 and S4). Clearly, future studies need to validate this speculation.

**Analysis 3: Relapse-related group differences for the association between the PIT effect and the OPRM1 polymorphism**

Only relapers but not abstainers showed a significant interaction between the PIT effect and the OPRM1 polymorphism. Moreover, only relapsing G+ carriers showed an increased PIT effect compared to abstainers, whereas there was no difference between the PIT effect in relapers and abstainers in G− carriers. One speculative interpretation of these findings is that there may be two pathways to relapse, and that these fundamentally differ with regard to the OPRM1 polymorphism and the PIT effect. On the one hand, in G+ carriers, the mechanisms driving PIT might also be related to relapse, whereas in G− carriers, these mechanisms could be less related to relapse. Our finding of an increased PIT effect in relapsing AD G+ carriers might also be relevant for precision medicine, particularly in the light of the ongoing discussion of the OPRM1 polymorphism as a potential biomarker for the effectiveness of naltrexone treatment (Chamorro et al., 2012; Hartwell et al., 2020; Oslin et al., 2003; Setiawan et al., 2012; Ziauddeen et al., 2016). Strikingly, treatment response to naltrexone was also particularly high in patients with AD classified as reward drinkers (Mann et al., 2018; Witkiewitz et al., 2019) and reduced craving, most notably in social drinkers, who had high positive alcohol expectancies (Palfai et al., 1999).

Similar considerations might be relevant to nalmefene, the MOP antagonist and partial κ-agonist, recently approved for the treatment of AD (Gual et al., 2013), with similarly conflicting results. According to a meta-analysis, the drug is able to improve behavioural outcomes in patients with AD (Mann et al., 2016),
while others show that it has a limited efficacy in AD therapy (Palpacuer et al., 2015; Soyka and Muller, 2017). Nalmefene administered in a modified ‘Go’/’No-Go’ paradigm mildly reduced vigor to alcoholic cues in patients with AD (Gal et al., 2019). However, no major differences were observed between the treatment group and the placebo group with respect to behavioural and neural correlates of approach/avoidance tendencies. Given our data, future studies could investigate whether naltrexone and/or nalmefene might be particularly effective in alcohol-dependent patients who are G+ carriers and additionally show large PIT effects.

**Outlook: How does OPRM1 influence neural reward processing?**

The neural correlates of PIT have been associated with relapse in AD within the mesolimbic reward system (Garbusow et al., 2016; Sekutowicz et al., 2019; Sommer et al., 2020) and could predict future drinking behaviour in adolescents (Sekutowicz et al., 2019). Recent studies have suggested a direct link between the OPRM1 polymorphism and the mesolimbic dopaminergic system. For instance, by using a mouse model of the OPRM1 A118G SNP, Popova et al. (2019) demonstrated that A- and G-allele carriers show significantly different regulation of mesolimbic dopaminergic firing. One potential underlying mechanism is that MOP receptors (which are affected by the OPRM1 polymorphism) mediate opioid-induced disinhibition of midbrain dopaminergic neurons (Jalabert et al., 2011; Jhou et al., 2012; Matsui et al., 2014). Recent work in rodents has proven that optogenetic manipulations of those dopaminergic neurons can bidirectionally modulate online action selection (Howard et al., 2017). Thus, we speculate that the OPRM1 polymorphism is associated with the extent to which Pavlovian stimuli functionally activate the mesolimbic dopaminergic system in AD. This speculation is in line with functional magnetic resonance imaging studies using cue reactativity paradigms in substance-dependent individuals. For instance, some studies suggest that AD G+ carriers display increased neural responses to alcohol-associated stimuli in mesocorticolimbic areas (Bach et al., 2015; Courtney et al., 2015; Filbey et al., 2008; but see Schacht et al., 2013). In line with this, humanised mice carrying the G+ allele of the OPRM1 polymorphism displayed increased striatal dopamine release in response to an intravenously infused alcohol dose (Ramchandani et al., 2011). Clearly, future studies should further investigate how the OPRM1 polymorphism affects the underlying neural mechanisms of the PIT effect in humans.

**Limitations**

The generalisability of our results is limited by the lack of preregistration, additional analyses designed after study protocol and the use of single gene analyses. The correlational nature of the analyses only allows speculation about causal relationships and needs to be further validated in a longitudinal design. Even though candidate genes as opposed to large-scale GWAS studies have come into disrepute, we believe that there is still a high relevance in connecting single genes and their respective pathways to specific neurocognitive processes and thus providing the opportunity for more specific interventions in precision medicine (Deb et al., 2010; Di Martino et al., 2020). Another limitation of our design is that the procedure used here to indicate Pavlovian learning (task phase 4) was not designed to detect between-group effects but instead served to identify subjects who did not learn the Pavlovian contingencies (Supplemental Information 8). Across all cohorts, subjects could almost perfectly identify the best Pavlovian stimuli, and these ceiling effects potentially lowered statistical power to detect differences in Pavlovian learning. Several studies across humans and animals have demonstrated that individuals who attribute incentive salience to reward predicting stimuli through Pavlovian conditioning (so called sign-trackers) will also show an increased PIT effect (Garofalo and di Pellegrino, 2015; Schad et al., 2019b). Future studies should therefore use more sensitive methods to identify sign-tracking humans (such as eye-tracking; Schad et al., 2019b) and test the role of the OPRM1 polymorphism in this phenomenon. One further limitation is the relatively small sample size of relapsers versus abstainers in analysis 3. Importantly, the group of G+ carriers that relapsed versus abstained was 16 versus 14, respectively. Thus, future stratification studies need to replicate our findings in larger sampling sizes, for example by oversampling G+ carriers in AD.

**Summary**

This study presents strong evidence for an association between the OPRM1 polymorphism and the PIT effect in both patients with AD and HCs. It is the first to show that the OPRM1 polymorphism modulates the extent to which Pavlovian stimuli exert control over behaviour and suggests a functional difference of this gene–behaviour interaction between relapsers and abstainers.

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Supplemental material

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References

Anton RF, Moak DH and Latham P (1995) The Obsessive Compulsive Drinking Scale: a self-rated instrument for the quantification of thoughts about alcohol and drinking behavior. *Alcohol Clin Exp Res* 19: 92–99.

Bach P, Vollstädt-Klein S, Kirsch M, et al. (2015) Increased mesolimbic cue-reactivity in carriers of the mu-opioid-receptor gene OPRM1 A118G polymorphism predicts drinking outcome: a functional imaging study in alcohol dependent subjects. *Eur Neuropsychopharmacol* 25: 1128–1135.

Barker JM, Torregrossa MM and Taylor JR (2012) Low prefrontal PSA-NLAM confers risk for alcoholism-related behavior. *Nat Neurosci* 15: 1356–1358.

Bates D, Mächler M, Bolker B, et al. (2015) Fitting linear mixed-effects models using lme4. *J Stat Softw* 67: arXiv:1406.5823.

Buchs JA, Kroll DS, Feldman DE, et al. (2019) Molecular imaging of opioid and dopamine systems: insights into the pharmacogenetics of opioid use disorders. *Front Psychiatry* 10: 626.

Chamorro A-J, Marcos M, Mirón-Canedo J-A, et al. (2012) Association of μ-opioid receptor (OPRM1) gene polymorphism with response to naltrexone in alcohol dependence: a systematic review and meta-analysis. *Addict Biol* 17: 505–512.

Chelnokova O, Laeng B, Eikemo M, et al. (2014) Rewards of beauty: the opioid system mediates social motivation in humans. *Mot Psychiatry* 14: 746–747.

Corbit LH and Janak PH (2007) Ethanol-associated cues produce general pavlovian-instrumental transfer. *Alcohol Clin Exp Res* 31: 766–774.

Courtney KE, Gahreman DG and Ray LA (2015) The effect of alcohol priming on neural markers of alcohol cue-reactivity. *Am J Drug Alcohol Abuse* 41: 300–308.

Deb I, Chakraborty J, Gangopadhyay PK, et al. (2010) Single-nucleotide polymorphism (A118G) in exon 1 of OPRM1 gene causes alteration in downstream signaling by mu-opioid receptor and may contribute to the genetic risk for addiction. *J Neurochem* 112: 486–496.

Dickinson A, Smith J and Mirenowicz J (2000) Dissociation of Pavlovian and instrumental incentive learning under dopamine antagonists. *Behav Neurosci* 114: 468–483.

Di Martino MT, Meschini S, Scotlandi K, et al. (2020) From single gene analysis to single cell profiling: a new era for precision medicine. *J Exp Clin Cancer Res* 39: 48.

Eikemo M, Brielle G, Willoch F, et al. (2017) Opioid modulation of value-based decision-making in healthy humans. *Neuropsychopharmacology* 42: 1833–1840.

Filbey FM, Ray L, Smolen A, et al. (2008) Differential neural response to alcohol priming and alcohol taste cues is associated with DRD4 VNTR and OPRM1 genotypes. *Alcohol Clin Exp Res* 32: 1113–1123.

Gal BI, Kilencz T, Albert A, et al. (2019) Mild effect of nalmefene on alcohol-deprived binge cue-reactivity in carriers of the mu-opioid-receptor gene OPRM1. *Addict Biol* 21: 719–731.

Garbusow M, Schad DJ, Sommer C, et al. (2014) Pavlovian-to-instrumental transfer in alcohol dependence: a pilot study. *Neuropsychobiology* 70: 111–121.

Garbalos S and di Pellegrino G. (2015) Individual differences in the influence of task-irrelevant Pavlovian cues on human behavior. *Front Behav Neurosci* 9: 163.

Gual A, He Y, Torup L, et al. (2013) A randomised, double-blind, placebo-controlled, efficacy study of nalmefene, as-needed use, in patients with alcohol dependence. *Eur Neuropsychopharmacol* 23: 1432–1442.

Guitart-Masip M, Duzel E, Dolan R, et al. (2014) Action versus valence in decision making. *Trends Cogn Sci* 18: 194–202.

Guitart-Masip M, Fuentemilla L, Bach DR, et al. (2011) Action dominates valence in anticipatory representations in the human striatum and dopaminergic midbrain. *J Neurosci* 31: 7867–7875.

Hartwell EE, Feinn R, Morris PE, et al. (2020) Systematic review and meta-analysis of the moderating effect of rs1799971 in OPRM1, the mu-opioid receptor gene, on response to naltrexone treatment of alcohol use disorder. *Addiction* 115: 1426–1437.

Heinz A, Reimold M, Wrase J, et al. (2005) Correlation of stable elevations in striatal mu-opioid receptor availability in detoxified alcoholic patients with alcohol craving: a positron emission tomography study using carbon 11-labeled carfentanil. *Arch Gen Psychiatry* 62: 57–64.

Hendershot CS, Claus ED and Ramchandani VA (2016) Associations of OPRM1 A118G and alcohol sensitivity with intravenous alcohol self-administration in young adults. *Addict Biol* 21: 125–135.

Howard CD, Li H, Geddes CE, et al. (2017) Dynamic nigrostriatal dopamine biases action selection. *Neuron* 93: 1436–1450 e1438.

Huys QJ, Cools R, Golzer M, et al. (2011) Disentangling the roles of approach, activation and valence in instrumental and Pavlovian responding. *PLoS Comput Biol* 7: e1002028.

Huys QJ, Tobler PN, Hasler G, et al. (2014) The role of learning-related dopamine signals in addiction vulnerability. *Prog Brain Res* 211: 31–77.

Jacobi F, Mack S, Gerschler A, et al. (2013) The design and methods of the mental health module in the German Health Interview and Examination Survey for Adults (DEGS1-MH). *Int J Methods Psychiatr Res* 22: 83–99.

Jalabert M, Boudry R, Courtin J, et al. (2011) Neuronal circuits underlying acute morphine action on dopamine neurons. *Proc Natl Acad Sci U S A* 108: 16446–16450.

Jhou TC, Xu SP, Lee MR, et al. (2012) Mapping of reinforcing and analgesic effects of the mu opioid agonist endomorphin-1 in the ventral midbrain of the rat. *Psychopharmacology (Berl)* 224: 303–312.

Kieffer BL and Gaveriaux-Ruff C (2002) Exploring the opioid system by gene knockout. *Prog Neurobiol* 66: 285–306.

Kong X, Deng H, Gong S, et al. (2017) Lack of associations of the opioid receptor mu 1 (OPRM1) A118G polymorphism (rs1799971) with alcohol dependence: review and meta-analysis of retrospective controlled studies. *BMC Med Genet* 18: 120.

Korb S, Götzendorfer SI, Sezen P, et al. (2019) Dopaminergic and opioidergic regulation of implicit and explicit wanting and liking of social and nonsocial rewards. *bioRxiv* 832196.

Laurent V, Leung B, Maidment N, et al. (2012) mu- and delta-opioid-related processes in the accumbens core and shell differentially mediate the influence of reward-guided and stimulus-guided decisions on choice. *J Neurosci* 32: 1875–1883.

LeBlanc KH, Maidment NT and Ostlund SB (2013) Repeated cocaine exposure facilitates the expression of incentive motivation and induces habitual control in rats. *PLoS One* 8: e61355.

LeBlanc KH, Ostlund SB and Maidment NT (2012) Pavlovian-to-instrumental transfer in cocaine seeking rats. *Behav Neurosci* 126: 681–689.

Lichtenberg NT and Wassum KM (2017) Amygdala mu-opioid receptors mediate the motivating influence of cue-triggered reward expectations. *Eur J Neurosci* 45: 381–387.

Mahler SV and Berridge KC (2012) What and when to ‘want’? Amygdala-based focusing of incentive salience upon sugar and sex. *Psychopharmacology (Berl)* 221: 407–426.

Mann K and Ackermann K (2000) Die OCDS-G: Psychometrische Kenntn. der deu-schen version der obsessive compulsive drinking scale. *Sucht* 46: 90–100.
Mann K, Roos CR, Hoffmann S, et al. (2018) Precision medicine in alcohol dependence: a controlled trial testing pharmacotherapy response among reward and relief drinking phenotypes. *Neuropsychopharmacology* 43: 891–899.

Mann K, Torup L, Sorensen P, et al. (2016) Nalmefene for the management of alcohol dependence: review on its pharmacology, mechanism of action and meta-analysis on its clinical efficacy. *Eur Neuropsychopharmacol* 26: 1941–1949.

Matsui A, Jarvie BC, Robinson BG, et al. (2014) Separate GABA afferents to dopamine neurons mediate acute action of opioids, development of tolerance, and expression of withdrawal. *Neuron* 82: 1346–1356.

Meule AV, Vöggele C and Kübler A (2011) Psychometrische evaluation der deutschen barratt impulsiveness scale – kurzversion (BIS-15). *Diagnostica* 57: 126–133.

Meyer PJ, Lovie V, Saunders BT, et al. (2012) Quantifying individual variation in the propensity to attribute incentive salience to reward cues. *PLoS One* 7: e38987.

Miller GA and Chapman JP (2001) Misunderstanding analysis of covariance. *A Clin Neurosci* 110: 40–48.

Mitchell JM, Tavares VC, Fields HL, et al. (2007) Endogenous opioid blockade and impulsive responding in alcoholics and healthy controls. *Neuropsychopharmacology* 32: 439–449.

Myrick H, Anton RF, Li X, et al. (2008) Effect of naltrexone and ondansetron on alcohol cue-induced activation of the ventral striatum in alcohol-dependent people. *Arch Gen Psychiatry* 65: 466–475.

O’Connor EC, Stephens DN and Crombag HS (2010) Modeling appetitive Pavlovian–instrumental interactions in mice. *Curr Protoc Neurosci* Chapter 8: Unit 8.25.

Oslin DW, Berrettini W, Kranzer HR, et al. (2003) A functional polymorphism of the mu-opioid receptor gene is associated with naltrexone response in alcohol-dependent patients. *Neuropsychopharmacology* 28: 1546–1552.

Ostlund SB, LeBlanc KH, Kosheleff AR, et al. (2014) Phasic mesolimbic dopamine signaling encodes the facilitation of incentive motivation produced by repeated cocaine exposure. *Neuropsychopharmacology* 39: 2441–2449.

Palfai T, Davidson D and Swift R (1999) Influence of naltrexone on cue-elicited craving among hazardous drinkers: the moderational role of positive outcome expectancies. *Exp Clin Psychopharmacol* 7: 266–273.

Palpacer C, Lavioille B, Bouassogne R, et al. (2015) Risks and benefits of nalmefene in the treatment of adult alcohol dependence: a systematic literature review and meta-analysis of published and unpublished double-blind randomized controlled trials. *PLoS Med* 12: e1001924.

Pecina S and Bertridge KC (2013) Dopamine or opioid stimulation of nucleus accumbens similarly amplify cue-triggered ‘wanting’ for reward: entire core and medial shell mapped as substrates for PIT enhancement. *Eur J Neurosci* 37: 1529–1540.

Persson E, Asutay E, Heilig M, et al. (2019) Variation in the mu-opioid receptor gene (OPRM1) does not moderate social-rejection sensitivity in humans. *Psychol Sci* 30: 1050–1062.

Popova D, Desai N, Blendy JA, et al. (2019) Synthetic regulation by OPRM1 variants in reward neurocircuitry. *J Neurosci* 39: 5685–5696.

Ramchandani VA, Umhau J, Pavon FJ, et al. (2011) A genetic determinant of the striatal dopamine response to alcohol in men. *Mol Psychiatry* 16: 809–817.

Ray LA and Hutchison KE (2004) A polymorphism of the mu-opioid receptor gene (OPRM1) and sensitivity to the effects of alcohol in humans. *Alcohol Clin Exp Res* 28: 1789–1795.

Saddoris MP, Stamatakis A and Carelli RM (2011) Neural correlates of Pavlovian-to-instrumental transfer in the nucleus accumbens shell are selectively potentiated following cocaine self-administration. *Eur J Neurosci* 33: 2274–2287.

Schacht JP, Anton RF, Voronin KE, et al. (2013) Interacting effects of naltrexone and OPRM1 and DAT1 variation on the neural response to alcohol cues. *Neuropsychopharmacology* 38: 414–422.

Scheid DJ, Garbusow M, Friedel E, et al. (2019a) Neural correlates of instrumental responding in the context of alcohol-related cues index disorder severity and relapse risk. *Eur Arch Psychiatry Clin Neurosci* 269: 295–308.

Scheid DJ, Rapp MA, Garbusow M, et al. (2019b) Dissociating neural learning signals in human sign- and goal-trackers. *Nat Hum Behav* 4: 201–214.

Sebold M, Schad DJ, Nebe S, et al. (2016) Don’t think, just feel the music: Individuals with strong pavlovian-to-instrumental transfer effects rely less on model-based reinforcement learning. *J Cogn Neurosci* 28: 985–995.

Sekutovicz M, Guggenmos M, Kuitunen-Paul S, et al. (2019) Neural response during Pavlovian-to-instrumental transfer predict alcohol relapse and young adult drinking. *Biol Psychiatry* 86: 857–863.

Setiawan E, Pihl RO, Benkelfat C, et al. (2012) Influence of the OPRM1 A118G polymorphism on alcohol-induced euphoria, risk for alcoholism and the clinical efficacy of naltrexone. *Pharmacogenomics* 13: 1161–1172.

Sloan ME, Klepp TD, Gowin JL, et al. (2018) The OPRM1 A118G polymorphism: converging evidence against associations with alcohol sensitivity and consumption. *Neuropsychopharmacology* 43: 1530–1538.

Sobell LC and Sobell MB (1992) Timeline follow-back: A technique for assessing self-reported alcohol consumption. In: R Litten and J Allen (eds) *Measuring Alcohol Consumption: Psychosocial and Biochemical Methods*. Totowa: Humana Press, 41–72.

Sommer C, Birkenstock J, Garbusow M, et al. (2020) Dysfunctional approach behavior triggered by alcohol-unrelated Pavlovian cues predicts long-term relapse in alcohol dependence. *Addiction Biology* 25: e12703.

Sommer C, Garbusow M, Junger E, et al. (2017) Strong seduction: impulsivity and the impact of contextual cues on instrumental behavior in alcohol dependence. *Transl Psychiatry* 7: e1183.

Soyka M and Muller CA (2017) Pharmacotherapy of alcoholism – an update on approved and off-label medications. *Expert Opin Pharmacother* 18: 1187–1199.

Stacy AW and Wiers RW. (2010) Implicit cognition and addiction: a tool for explaining paradoxical behavior. *Annu Rev Clin Psychol* 6: 551–575.

Swart JC, Frobose MI, Cook JL, et al. (2017) Catecholaminergic channel uncovers distinct Pavlovian and instrumental mechanisms of motivated (in)action. *Elife* 6.

Talini D, Seymour B, Dayan P, et al. (2008) Human Pavlovian-instrumental transfer. *J Neurosci* 28: 360–368.

Van Den Wildenberg E, Wiers RW, Dessers J, et al. (2007) A functional polymorphism of the mu-opioid receptor gene (OPRM1) influences cue-induced craving for alcohol in male heavy drinkers. *Alcohol Clin Exp Res* 31: 1–10.

Van Steenbergen H, Eikemo M and Leknes S (2019) The role of the opioid system in decision making and cognitive control: a review. *Cogn Affect Behav Neurosci* 19: 435–458.

Van Timmeren T, Quail SL, Balleine BW, et al. (2020) Intact corticostriatal control of goal-directed action in alcohol use disorder: a Pavlovian-to-instrumental transfer and outcome-devaluation study. *Sci Rep* 10: 4949.

Way BM, Taylor SE and Eisenberger NI (2009) Variation in the mu-opioid receptor gene (OPRM1) is associated with dispositional and neural sensitivity to social rejection. *Proc Natl Acad Sci U S A* 106: 15079–15084.

Weber SC, Beck-Schimmer B, Kajdi ME, et al. (2016) Dopamine D2/3- and mu-opioid receptor antagonists reduce cue-induced responding and reward impulsivity in humans. *Transl Psychiatry* 6.

Wiers RW, Rinck M, Diets M, et al. (2009) Relatively strong automatic appetitive action-tendencies in male carriers of the OPRM1 G-allele. *Genes Brain Behav* 8: 101–106.

Witkiewitz K, Roos CR, Mann K, et al. (2019) Advancing precision medicine for alcohol use disorder: replication and extension of reward drinking as a predictor of naltrexone response. *Alcohol Clin Exp Res* 43: 2395–2405.
Wittchen HU and Pfister H (1997) DIA-X-Interviews: Manual für Screening-Verfahren und Interview; Interviewheft. Frankfurt: Swets & Zeitlinger.

World Health Organization (WHO) (2014) Global Status Report on Alcohol and Health. Geneva: World Health Organization.

Ziauddeen H, Nestor LJ, Subramaniam N, et al. (2016) Opioid antagonists and the A118G polymorphism in the mu-opioid receptor gene: effects of GSK1521498 and naltrexone in healthy drinkers stratified by OPRM1 genotype. Neuropsychopharmacology 41: 2647–2657.