

Decision- and feedback-related brain potentials reveal risk processing mechanisms in patients with alcohol use disorder

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Abstract

Individuals with alcohol use disorder (AUD) are aware of the risks of alcohol abuse yet continue risky drinking. Research indicates that dysfunctional decision processes and trait variables such as impulsivity contribute to this awareness-behavior discrepancy. The present study focused on decision-related versus feedback-related processes as potential contributors to decision making in AUD by examining the relationship between decision choices and decision- and feedback-related ERP phenomena in the balloon analogue risk task (BART). $N = 39$ AUD and $n = 35$ healthy comparison participants (HC) performed the BART modified for EEG assessment. In each of 100 runs, participants made a series of choices about whether to pump up a virtual balloon, which popped pseudorandomly, ending the run. Alternatively, participants ended the run by pressing a “cash-out” button. Each pump not producing a pop provided .05 €; popping resulted in loss of the run’s accumulated gain. Groups made similar choices, though AUD responded more slowly. The decision P3 200–400 ms after decision prompt (balloon) was larger in AUD than in HC, and decision P3 enhancement on high-risk trials predicted choices to pump. Feedback-related negativity (FRN) after loss (relative to cash out) feedback was smaller in AUD than in HC, suggesting indifference to negative feedback. In AUD, high impulsivity was associated with risk-modulated decision P3 but not FRN. Results indicate atypical decision- and feedback-related processes that could contribute to difficulties in engaging with daily challenges effectively.

KEYWORDS

alcohol use disorder, decision risk, ERP P3, FRN, outcome feedback

1 | INTRODUCTION

1.1 | Decision making and alcohol use

Research has characterized individuals with alcohol use disorders (AUD) as often participating in risky drinking despite knowledge of negative physical, social, and legal consequences (Ernst & Paulus, 2005; Fein & Chang, 2008;

Fein, Klein, & Finn, 2004; Miranda, MacKillop, Meyerson, Justus, & Lovallo, 2009). This risk bias is often discussed in the framework of dysfunctional decision behavior (Bechara et al., 2001; Bjork, Hommer, Grant, & Danube, 2004; Euser, Van Meel, Snelleman, & Franken, 2011). Given that adaptive decision behavior is guided by balancing risks of potential negative and positive consequences (Brown et al., 2015)

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or weighing immediate rewards against long-term negative consequences (Mazas, Finn, & Steinmetz, 2000), this risky bias suggests dysfunctional evaluation of risk and/or outcome in AUD. Evidence from a variety of experimental tasks indicates faster and riskier choices associated with AUD, whether in abstinent AUD, adolescents at risk, offspring of AUD parents, or individuals with other substance use disorders (Erskine-Shaw, Monk, Qureshi, & Heim, 2017; Euser, Evans, Greaves-Lord, Huizink, & Franken, 2013; Euser, Greaves-Lord et al., 2013). Several moderators of dysfunctional decision behavior in AUD have been proposed, such as optimistically biased perception of one's own risk (Klepper, Odenwald, & Rockstroh, 2016), indifference to the negative consequences of alcohol consumption (Kamarajan et al., 2010), and trait impulsivity (Dick et al., 2010; Kumar, Kumar, & Benegal, 2018), but the impact of these moderators and their interactions are not sufficiently understood.

1.2 | ERPs as indices of decision-making processes

A common theoretical framework for decision making describes risk-taking behavior (defined as risky decisions) as determined primarily by a combination of perception (decision phase: defined as evaluation of outcome options and their valence and prediction of chance of winning) and outcome evaluation (outcome phase: defined as prediction error and reward valuation; Paulus, 2005; Steffen, Rockstroh, Wienbruch, & Miller, 2011). Complementing measurement of risky overt behavior, brain activity manifested in ERPs during the decision and the outcome phases has often been measured to study these processes (Chandrakumar, Feuerriegel, Bode, Grech, & Keage, 2018; Steffen et al., 2011). For example, evidence from various experimental tasks has characterized the decision phase as producing a positive ERP component 200–400 ms after onset of the decision prompt (usually labeled as N2/P3 or decision P3; Hassall, Holland, & Krigolson, 2013; Polich, 2007; Steffen et al., 2011; Wang, Zheng, Huang, & Sun, 2015). Decision P3 varies with risk level (i.e., the chance of winning) and with monetary gain (i.e., outcome value; He, Guan, Zhao, & Cao, 2013; Schuermann, Endrass, & Kathmann, 2012). High-risk decisions, as indicated by high-valued choices with less predictable outcomes, were associated with a larger decision P3 than were low-risk decisions (Gu, Zhang, Luo, Wang, & Broster, 2018; Hassall et al., 2013; Kiat, Straley, & Cheadle, 2016). P3 amplitude also predicted whether participants subsequently made a risky or a safe choice on a given trial (Gu et al., 2018). To date, smaller P3 in AUD and in individuals at risk of developing AUD has been reported in oddball tasks or go/no-go tasks (Euser et al., 2012; Hada, Porjesz, Chorlian, Begleiter, & Polich, 2001; Hill et al., 1999; Kamarajan et al., 2005; Oscar-Berman, 1987; Pfefferbaum, Ford, White,

& Mathalon, 1991). These studies have not simultaneously varied the level of risk and prompt outcome prediction and valuation, which limits understanding of altered risk processing in AUD.

ERP components emerging in the outcome phase have been related to different processes prompted by outcome feedback such as prediction error and reward evaluation. The negative component 200–350 ms after feedback stimulus onset is commonly labeled feedback-related negativity (FRN), referring to its larger amplitude following loss than win feedback, or prediction error-related negativity (fERN), referring to its amplitude modulation by unexpected loss versus win (feedback-related negativity, FRN, FN, fERN; Averbeck, 2017; Baker, Stockwell, Barnes, & Holroyd, 2011; Crowley et al., 2009; Fein & Chang, 2008). The latter refers to reinforcement learning (Holroyd & Coles, 2002) and identifies FRN after loss feedback as an index of prediction error (Sambrook & Goslin, 2015). The comparison of expected and actual outcomes is thought to be processed in the anterior cingulate cortex (ACC), which, via dopaminergic activity, mediates adaptation of behavior to sustain task performance (Umemoto, Inzlicht, & Holroyd, 2019; Weiss et al., 2018). FRN/fERN have also been associated with reward valuation, as FRN varies with higher affective response to negative feedback (Santesso, Bogdan et al., 2011).

The FRN overlaps temporally with positive deflections. When scored from the difference waveform subtracting unexpected negative from unexpected positive feedback, the relative positive deflection, labeled reward positivity (RewP), is considered to reflect suppression of a FRN (Baker & Holroyd, 2008; Chandrakumar et al., 2018; Proudfit, 2015; Proudfit, Bress, Foti, Kujawa, & Klein, 2015). The RewP is associated with reward sensitivity, as it varies with self-reported and behavioral measures of reward sensitivity (Bress & Hajcak, 2013). The RewP can also be associated with reward prediction error when outcome is worse than expected (negative prediction error) or better than expected (positive prediction error; see also Baker, Stockwell, Barnes, Haesevoets, & Holroyd, 2016; Baker, Wood, & Holroyd, 2016; Parvaz et al., 2015). A distinct positive component peaking around 300 ms after feedback onset (feedback P3; Hajcak, Holroyd, Moser, & Simons, 2005; Yeung & Sanfey, 2004) has been associated primarily with reward valuation.

FRN and RewP are altered in individuals with psychiatric disorders, including AUD and other substance use disorders. Yet, compared to consistent evidence of blunted RewP (Hixson, Burkhouse, Gorka, & Klumpp, 2019; Proudfit et al., 2015) or FRN (Foti, Carlson, Sauder, & Proudfit, 2014) in internalizing psychopathology and of accentuated RewP in externalizing psychopathology such as habitual smokers (Potts, Bloom, Evans, & Drobles, 2014) and problem gamblers (Hewig et al., 2010), evidence about reward processing in

AUD is inconclusive. A blunted FRN after negative feedback has consistently been documented in AUD (Kamarajan et al., 2010) and in treatment-naïve problem drinkers (Fein & Chang, 2008). Whereas Hixson et al. (2019) reported less RewP attenuation in a sample of MDD patients with history of comorbid AUD than in MDD patients without comorbid AUD, Baker, Wood and colleagues (2016) found blunted RewP upon monetary reward but augmented RewP upon addiction-associated reward in students with substance use disorders.

Results for altered feedback P3 in AUD are diverse, such as being smaller in AUD (Kamarajan et al., 2010) and in at-risk adolescents with a parental history of substance use disorder (Euser, Greaves-Lord et al., 2013) and larger in treatment-naïve problem drinkers (Fein & Chang, 2008). Taken together, whether and how outcome processing is compromised in AUD remains unknown.

Reward and decision processing may be closely related to trait variables such as impulsivity or risk-taking propensity (Leicht et al., 2013; Vaughan et al., 2019) and thus prominent features of AUD (Proudfit, 2015; Proudfit et al., 2015). Reward sensitivity has even been described as an aspect of impulsivity (Dawe, Gullo, & Loxton, 2004; Franken & Muris, 2006). Indeed, impulsivity, sensation seeking, risk-taking propensity, and depression have been found to modify decision making and risk processing in AUD (Kamarajan et al., 2015; Proudfit, 2015; Proudfit et al., 2015; Santesso & Segalowitz, 2009). Impulsive decision making in AUD (Camchong, Endres, & Fein, 2014; Kovács, Richman, Janka, Maraz, & Andó, 2017) has been inferred from the positive relationship between risky choices in experimental tasks and alcohol consumption (e.g., Bechara et al., 2001; Bjork et al., 2004; Euser et al., 2011). Courtney et al. (2012) identified impulsive risky decisions (in delay discounting and other experimental tasks) as major predictors of alcohol use in a community sample of problem drinkers (see also Mitchell, Fields, D'Esposito, & Boettiger, 2005 for abstinent AUD), with risky decisions varying with alcohol addiction severity and trait impulsivity (Mitchell et al., 2005). Using structural equation modeling, Nees et al. (2012) found self-rated risk-taking behavior (measured in the Cambridge gambling task), impulsivity, novelty seeking, and extraversion to explain more variance in alcohol consumption and early onset of drinking than did fMRI brain activation in a decision task including reward processing. This evidence suggests impulsivity as a moderator of decision making in the present study.

1.3 | The present study

Available literature has generally assessed decision- and feedback-related processes separately. However, both processes have been theoretically linked in the framework of reinforcement learning and behavioral control and the contribution of ACC and dopaminergic system to this link

(Holroyd & Coles, 2002). A systematic assessment of how both processes operate together in AUD should substantiate such conceptualization and help to explain why individuals with AUD engage in risky behavior despite their knowledge of risk. The present study examined ERP components tracking decision processes and outcome feedback processes within the same task in AUD and healthy comparison participants (HC), with impulsivity as potential trait moderator. The relationships between decision-phase and outcome-phase processes manifested in ERP components were examined in AUD and HC concerning the primary issue of whether abnormal risky decisions involve a failure at the decision phase (including processes such as reward prediction) and/or at the outcome phase (including prediction error and reward valuation), considering the modulation of these processes by impulsivity. A variant of the balloon analogue risk task¹ (BART; Lejuez et al., 2002, 2003), modified for EEG, was used for the assessment of risk-taking proneness (Lejuez et al., 2003) and particularly for distinguishing decision and feedback/outcome-related processes (Gu et al., 2018; Kiat et al., 2016). Its validity has been demonstrated in healthy individuals (Wallsten, Pleskac, & Lejuez, 2005) and in AUD (Fein & Chang, 2008) based on self-reports of risk behavior such as smoking, gambling, and unprotected sexual encounters (Lejuez et al., 2003) and based on relationships between sensation-seeking and/or impulsivity and decision behavior (Lauriola, Panno, Levin, & Lejuez, 2013; Lejuez et al., 2002). Risky decisions were defined, following Lejuez et al. (2002), as (a) the average number of pumps per trials that did not produce a pop, and (b) the number of popped balloons. Specifically, the present analyses targeted decision P3 as an index of reward prediction, and FRN and feedback P3 as indices of the evaluation of outcome expectancy and reward value (monetary gain or loss). Specific hypotheses were.

1. AUD more often choose to inflate the balloon and respond faster than HC, indicating high inclination toward risky decisions (higher risk of balloon explosions and monetary loss).
2. Decision P3 is larger before high-risk choices than before low-risk choices, but AUD exhibit smaller decision P3 than HC and less variation with risk level, indicating poorer risk evaluation.
3. FRN and feedback P3 are larger for loss than for cash-out feedback, but AUD show less differentiation in response to such feedback, indicating indifference to negative outcome. (A sequential decision task like the BART, the decision prompt [of an unpopped balloon] also provides

¹In the BART, participants make a series of choices to pump up a balloon on a computer screen; each pump choice yields a monetary reward unless the balloon bursts, with loss of accumulated gain; see Method for detailed task description.

“win” or reward feedback, which might prompt a RewP. This was explored in a secondary analysis on RewP/FRN determined from the difference wave between these win trials and loss trials. Because of inconsistent results, no directional hypothesis regarding group differences of RewP was phrased.)

4. Decision-related processes affect outcome-related processes in that (a) decision P3 predicts task performance (choices and reaction time), and (b) decision P3 predicts FRN. If Hypotheses 2 and 3 confirm compromised decision-related ERP components in AUD, (c) these relationships are weaker in AUD than in HC.

Some tests of Hypotheses 2, 3, and 4 were repeated with impulsivity included as a covariate, to see whether relevant variance remained in the group variable with impulsivity partialled out. For example, we expected that higher impulsivity in AUD than in HC would modulate the hypothesized group differences, such that high impulsivity varies with attenuated decision P3 and FRN.

2 | METHOD

2.1 | Participants

Thirty-nine in-patients with the diagnosis of AUD (DSM-V 309, ICD-10 F10) were recruited for the present study (see Table 1 for demographic information). In-patients participated in a targeted treatment program at the local Center for Psychiatry (ZfP Reichenau) after detoxification. AUD with a history of neurological condition or disorder, including epilepsy or head trauma with loss of consciousness, were not included. At the time of assessment, AUD were not consuming any alcohol² and were not receiving anticraving medication. The AUD sample was compared to 35 HC participants recruited from the local community through advertisements at university and community meeting places as well as among acquaintances. Individuals with a history of neurological or psychiatric disorder (including AUD), assessed by the M.I.N.I. (Ackenheil, Stotz-Ingenlath, Dietz-Bauer, & Vossen, 1999), were excluded. Samples did not differ in gender balance or age. HC had more years of school education. Introducing education as covariate in the analyses of decision choices and ERP did not alter the results.

Impulsivity was assessed using the German short version of the I-8 impulsivity scale (Kovaleva, Beierlein, Kemper, & Rammstedt, 2012) that follows the UPPS model of four dimensions of impulsivity (urgency, perseverance,

TABLE 1 Participant demographics

	AUD	HC	Test of differences
Age, years, <i>M (SD)</i>	43.2 (8.4)	42.7 (9.9)	$F = 0.06, p = .809$
Education, years, <i>M (SD)</i>	10.2 (1.6)	12.2 (1.4)	$F = 32.15, p < .001$
Gender, % male	72	66	$\chi^2 = 0.32, p = .573$

Abbreviations: AUD, patients with alcohol use disorders; HC, healthy comparison participants; *M*, mean; *SD*, standard deviation.

premeditation, sensation seeking; Whiteside, Lynam, Miller, & Reynolds, 2005). Items are evaluated on a 5-point Likert scale ranging from 1 (*totally disagree*) to 5 (*totally agree*). Higher impulsivity is reflected in higher scores on urgency and sensation-seeking items and lower scores on perseverance and premeditation items. The I-8 has been proven to be a valid and reliable instrument to assess impulsivity in relevant samples (Kovaleva et al., 2012). AUD showed higher impulsivity on all four impulsivity subscales (multivariate $F(4, 68) = 10.96, p < .001, \eta_p^2 = .39$; I-8 not available for one AUD). The urgency subscale was then selected as the index of impulsive behavior, because those items have the strongest conceptual relationship with reward sensitivity. Urgency was assessed as the means of two items: (a) “Sometimes I do things impulsively that I shouldn’t do,” and (b) “I sometimes do things to cheer myself up that I later regret.” As expected, AUD scored higher in urgency, $F(1, 71) = 40.25, p < .001, \eta_p^2 = .36$.

The Edinburgh Handedness Questionnaire (EHQ, Oldfield, 1971) indicated right-handedness in 28 of the 39 AUD and 31 of the 35 HC.³ Four AUD were ambidextrous or left-handed (laterality quotient between +60 and –100). All participants had normal or corrected-to-normal vision. Participants received 25.78 € on average depending on their success in the BART (including 10 € bonus for participation). Prior to the study, participants were informed about the purpose of the study and provided written informed consent according to the Declaration of Helsinki. The study protocol was approved by the Ethics Review Board of the University of Konstanz.

2.2 | BART

The BART was modified to facilitate EEG recording and to distinguish decision and outcome processing. Stimuli were presented via Presentation software (Neurobehavioral Systems Inc., Albany, CA). On each of 100 runs, participants chose to inflate a virtual balloon in steps by 1 to 12 button presses. Across runs, balloons popped on the 3rd to 12th

²In the AUD treatment program, patients were not allowed to consume alcohol or illegal drugs. Regular urine and breathalyzer tests after weekends and spot checks during the week by clinic staff served to foster abstinence.

³EHQ data of 4 HC and 7 AUD patients were unavailable.

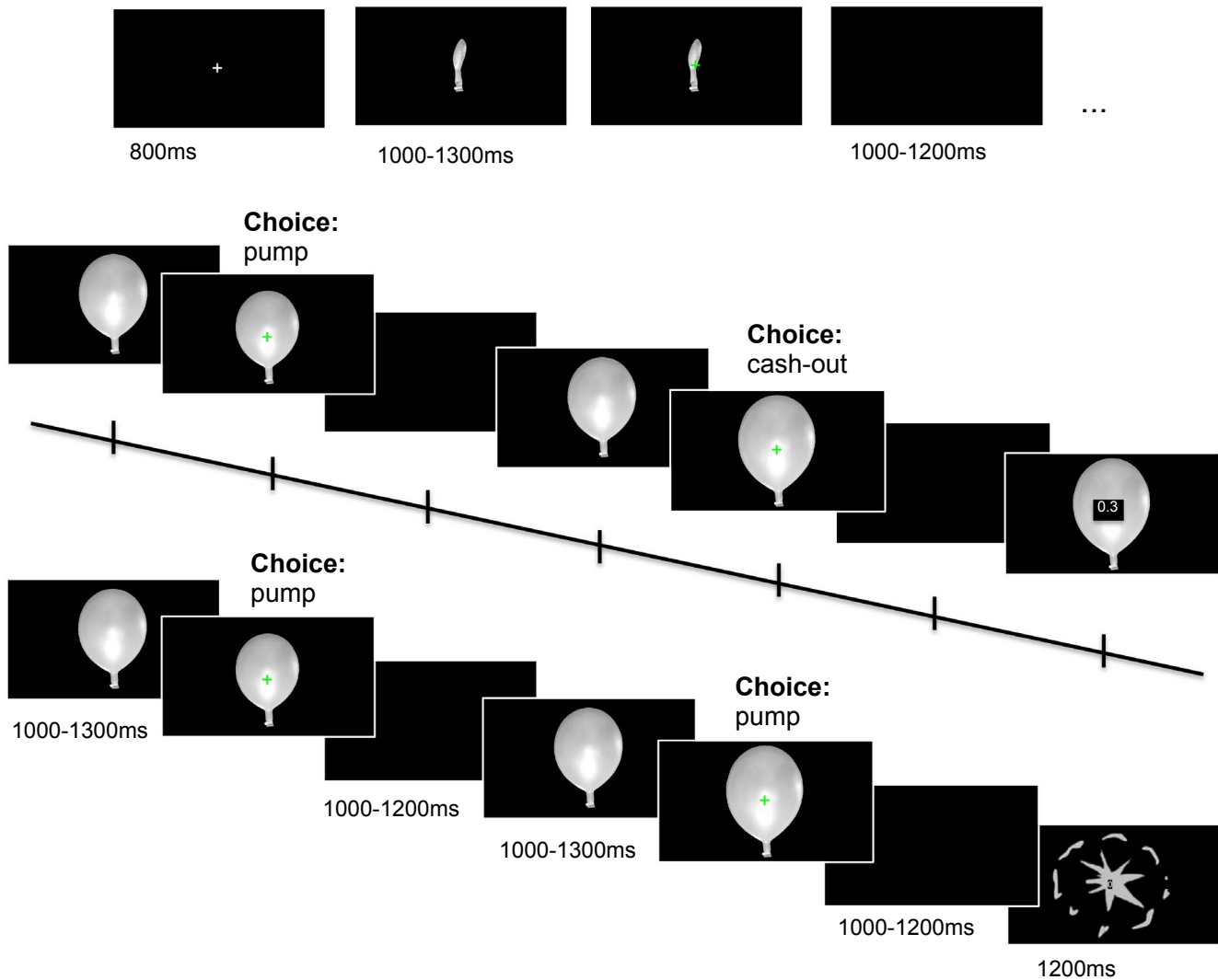


FIGURE 1 Temporal sequence of visual stimulus presentation during a typical run. Top: Each run starts with an 800-ms fixation cross, followed by a balloon that serves as the decision prompt presented for 1,000–1,300 ms (jittered across trials) before a green cross (response prompt) appears in the middle of the balloon that serves as the decision prompt (left mouse key press: pump; right mouse key press, cash-out). Middle: Example of run with cash-out decision after a series of pumps: the pump decision is followed by a 1,000–1,200 ms (jittered) blank screen, after which the next-sized balloon is presented for 1,000–1,300 ms (jittered) before the green cross appears in the middle of the balloon (response prompt). The outcome feedback is presented for 1,200 ms after the cash-out response. Bottom: Example of run ended by balloon popping

balloon size (pseudorandomly from a uniform distribution), ending the run (Helfinstein et al., 2014). Participants chose between pumping and ending the run by pressing a “pump” button or “cash-out” button. Each pump choice not resulting in balloon popping was rewarded with .05 €, whereas popping resulted in loss of the run’s accumulation. Visual (€) and auditory (popping or cash register sound) feedback informed the participant of the outcome 1,000 ms after each response.

Each run (see Figure 1) started with the 800 ms presentation of a white fixation cross on the computer screen (about 90 cm from the participant’s eyes), followed by the picture of a limp (minimal size) balloon (decision prompt). Participants were instructed to decide whether to pump up the balloon when a green cross appeared at the center of the balloon.

The green cross (response prompt) appeared 1,000–1,300 ms (jittered) after the decision prompt (balloon) onset in order to limit movement artifact in the ERP. Participants were instructed to press the left mouse key for pump and the right mouse key for cash-out. Each response was followed by a 1,000–1,200 ms interval (black screen, jittered) before visual and acoustic feedback was provided: pump decisions resulted either in the 1,000–1,300 ms presentation of the next larger balloon together with the sound of inflation or in the 1,200 ms presentation of a popped balloon picture together with a popping sound and a “0” icon indicating the loss of accumulated gain (loss feedback). Cash-out decisions led to the 1,200 ms picture of the accumulated reward in € together with the sound of a cash register. The next run started after

a 1,000–1,200 ms (jittered) interval. At the end of 100 runs, the 10 € bonus was added to the accumulated monetary gain. Addressing Hypothesis 1, choice types were examined with a 2×3 Group \times Risk analyses of variance (ANOVA). Here and below, significant interactions were dissected with simple-effects ANOVAs. Reported p values for effects involving the three-level risk factor reflect Huynh-Feldt epsilon correction.

2.3 | Data acquisition and analysis

Following Lejuez et al. (2002), decision behavior measures were (a) the average number of pumps per run that did not produce a pop, and (b) the number of popped balloons. Reaction time (RT) was measured from response prompt to response key press in milliseconds. Addressing Hypothesis 1, performance measures were evaluated with 2×3 Group \times Risk ANOVAs (levels of risk defined below).

The EEG was recorded in an electrically shielded room with a 128-channel ANT Neuro system using equidistant hexagonal Waveguard caps. EEG was filtered DC–204.8 Hz and sampled at 1,024 Hz. Each channel was referenced to the average of all other electrodes. Following acquisition guidelines (Keil et al., 2014), electrode impedances were kept below 30 k Ω . Data analysis was conducted using the open-source MATLAB Fieldtrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011) and SPSS. After band-pass filtering 0.5–40 Hz, data were epoched from 500 ms before to 1,000 ms after the onset of the respective stimulus (decision prompt and feedback) and baseline adjusted using 500-ms prestimulus intervals. Trials contaminated with movement artifact based on visual inspection were discarded. Independent component analysis (Jung et al., 2001) was used to remove components associated with cardiac activity and eye movements.

Addressing Hypothesis 2, the decision P3 was scored as the positive peak 200–400 ms after the decision prompt within the 1,500-ms epoch in 13 central-parietal electrodes near Cz and Pz of the 10-20 system. Variation in decision P3 with group and risk was assessed by selection of low-risk and high-risk trials for each participant: from all trials on which pump choices did not produce a balloon pop, 50 trials with balloon size 3 were randomly selected as representing low risk, and the 50 trials per participant with the largest balloon sizes were defined as high risk. One HC was excluded from analyses due to having only one usable low-risk trial, no high-risk trials, and no loss trials, leaving 35 HC participants. In addition, decision P3 was scored from all trials that ended a run by cash-out choice. Groups did not differ in number of trials from which decision P3 was scored.⁴ In parallel with

choice and RT, decision P3 was examined with a 2×3 Group \times Risk ANOVA.

Addressing Hypothesis 3, the FRN was scored as the peak-to-peak difference (see Hajcak, Moser, Holroyd, & Simons, 2006; Holroyd, Nieuwenhuis, Yeung, & Cohen, 2003) in the waveform average of five frontal electrodes around Fz (10-20 system) 200–350 ms, specifically between the negative peak and the preceding positive peak (starting 100 ms after the onset of the feedback stimulus), on trials providing feedback ending a run (cash-out, loss). An additional exploratory analysis operationalized reward positivity (RewP) as the maximum amplitude of the difference wave between the ERP on win trials within a run (i.e., next-sized balloon after pump decision signaling successful decision and monetary gain, the trials were labeled win feedback) and the ERP prompted by loss feedback (i.e., popped balloon). The difference wave was determined for the interval 200–350 ms after respective feedback stimulus (next-sized balloon or pop) from the average waveform of five frontal electrodes around Fz (10-20 system). Difference waveforms were based on an equal number of trials, in that for each participant the number of win trials (balloon) was adjusted to the number of loss trials (pop). (For illustration: for trials with popped balloon at size 4, an equal number of trials with size 4 balloons that did not pop was selected). The variation of RewP with group was examined by one-factor ANOVA.

The feedback P3 was scored as the positive peak in the average of 13 central-parietal electrodes (see decision P3) 200–500 ms following the feedback ending a run, relative to 500 ms prefeedback baseline. The variation of FRN and feedback P3 with group and outcome condition was examined with a 2×2 Group \times Outcome ANOVA. Groups did not differ in the average number of artifact-free trials from which FRN and feedback P3 were scored.⁵

The impact of impulsivity on risk decisions and ERP scores was evaluated by repeating the ANOVAs described above with urgency score added as a covariate.

Addressing Hypothesis 4, the relationship of decision-related processes (decision P3) to decision choices, RT (a), and feedback-related FRN (b) was examined by hierarchical regression. Separate analyses regressed the average number of balloons that did not pop, RT, and FRN onto the predictors group (Step 1), impulsivity (Step 2), the difference in decision P3 amplitude (high-risk minus low-risk trials) prior to pump decisions (Step 3), and the interaction of group and decision P3 difference (Step 4).

⁴Mean \pm SD, low risk: AUD, 49.3 \pm 3.2, HC, 49.5 \pm 2.2; high risk: AUD, 47.3 \pm 8.9, HC, 46.4 \pm 9.4; cash-out: AUD, 50.7 \pm 16.0, HC, 55.4 \pm 11.5 (group p = .257; risk $F(2, 144)$ = 6.74, p = .008, η^2 = .086; Group \times Risk, p = .231).

⁵Mean \pm SD, cash-out: AUD, 54.7 \pm 12.7, HC, 57.9 \pm 12.4; loss: AUD, 31.3 \pm 10.3, HC, 31.4 \pm 8.7 (group $F(1, 72)$ = 2.17, p = .145; outcome $F(1, 72)$ = 113.68, p < .001; Group \times Outcome, F < 1).

TABLE 2 Decision choice and decision RT descriptives and simple-effects ANOVAs

	AUD, <i>M</i> (<i>SD</i>)	HC, <i>M</i> (<i>SD</i>)	<i>F</i>	Effect size
Average number of pumps	5.2 (1)	5.2 (1)	0.04	.00
Number of popped balloons	37.1 (12.5)	36.1 (10.4)	0.14	.00
RT cash-out decisions	454.4 (216.5)	338.9 (109.3)	8.11*	.10
RT low-risk decisions	547.0 (258.0)	380.8 (137.2)	11.58**	.14
RT high-risk decisions	590.8 (306.3)	443.8 (214.7)	5.59*	.07

Note: AUD pressed the pump button (mean \pm *SD*) 311.2 \pm 28 times and HC 321.3 \pm 25.1 times before they decided to cash out, $F(1, 71) = 2.64, p = .109$.

Abbreviations: AUD, patients with alcohol use disorders; HC, healthy comparison participants; *M*, mean; RT, reaction time; *SD*, standard deviation.

* $p < .05$; ** $p \leq .001$.

2.4 | Parametric study controlling for visual input confound

As visual stimulus parameters such as balloon size may affect cortical responses, a separate study with an independent sample of 10 HC included an additional condition in which key presses gradually deflated an originally inflated balloon (Kiat et al., 2016). Fifty trials starting with an inflated balloon were mixed pseudorandomly with 50 trials starting with a limp balloon (as in the original BART). The distribution of popped balloons was the same in both conditions. A 5 (Balloon Size) \times 2 (Condition: inflation, deflate) repeated measures ANOVA found no significant differences in decision choice and decision P3 between inflating and deflating versions, so any impact of physical parameters on the results reported below seems unlikely (Weiss, unpublished thesis, 2017).

3 | RESULTS

3.1 | Behavioral performance

Disconfirming Hypothesis 1, Table 2 shows that AUD and HC were similar in choice behavior: number of pumps per run and number of popped balloons. Tables 2 and 3 show that AUD were slower to respond than HC. However, the two groups showed the same effects of risk level: responses were fastest when making cash-out decisions and slowest when making high-risk decisions. As a manipulation check, these results confirm that the choice conditions differed as intended and were similarly effective in the two groups.

3.2 | Decision P3

Figure 2 illustrates ERP waveforms at central-parietal electrodes time-locked to the onset of the decision prompt

TABLE 3 Decision RT ANOVA and pairwise comparisons

	<i>F</i>	Effect size
Group	9.30*	.11
Risk level	22.36**	.24
Group \times Risk	1.00	.01
Cash-out vs. low-risk	11.88**	.14
Low-risk vs. high risk	14.69**	.17
High-risk vs. cash-out	35.86**	.33

Note: Effect size = partial η^2 .

* $p < .05$; ** $p \leq .001$.

(balloon onset). The decision P3 peaking 200–350 ms after the decision prompt was larger in AUD than in HC, $F(1, 72) = 9.85, p = .002, \eta_p^2 = .12$. This is in contrast to the expected (Hypothesis 2) smaller decision P3 indicating poorer risk evaluation in AUD. However, as in overt behavior, the two groups showed similar effects of risk, with decision P3 largest for cash-out trials, followed by high- then low-risk trials, in line with Hypothesis 2 (risk, $F(2, 144) = 58.51, p < .001, \epsilon = .90, \eta_p^2 = .45$; Group \times Risk, $F(2, 144) = 1.58, p = .211, \epsilon = .90, \eta_p^2 = .02$). Table 4 provides means and pairwise comparisons. In parallel with the group effect, impulsivity, which was highly correlated with group, was related to decision P3, as more impulsive individuals showed larger decision P3 amplitudes (impulsivity, $F(1, 70) = 12.97, p < .001, \eta_p^2 = .16$); this absorbed the group effect (group, $F(1, 70) = .58, p = .450, \eta_p^2 = .01$; Group \times Risk, $F(2, 140) = .01, p = .983, \eta_p^2 = .00$). The Impulsivity \times Risk interaction approached significance, $F(2, 140) = 2.71, p = .076, \eta_p^2 = .04$, and was explained via post hoc simple-effects contrasts by larger decision P3 difference prior to high- than prior to low-risk decisions in individuals high in trait impulsivity, $F(1, 70) = 5.32, p = .024$.

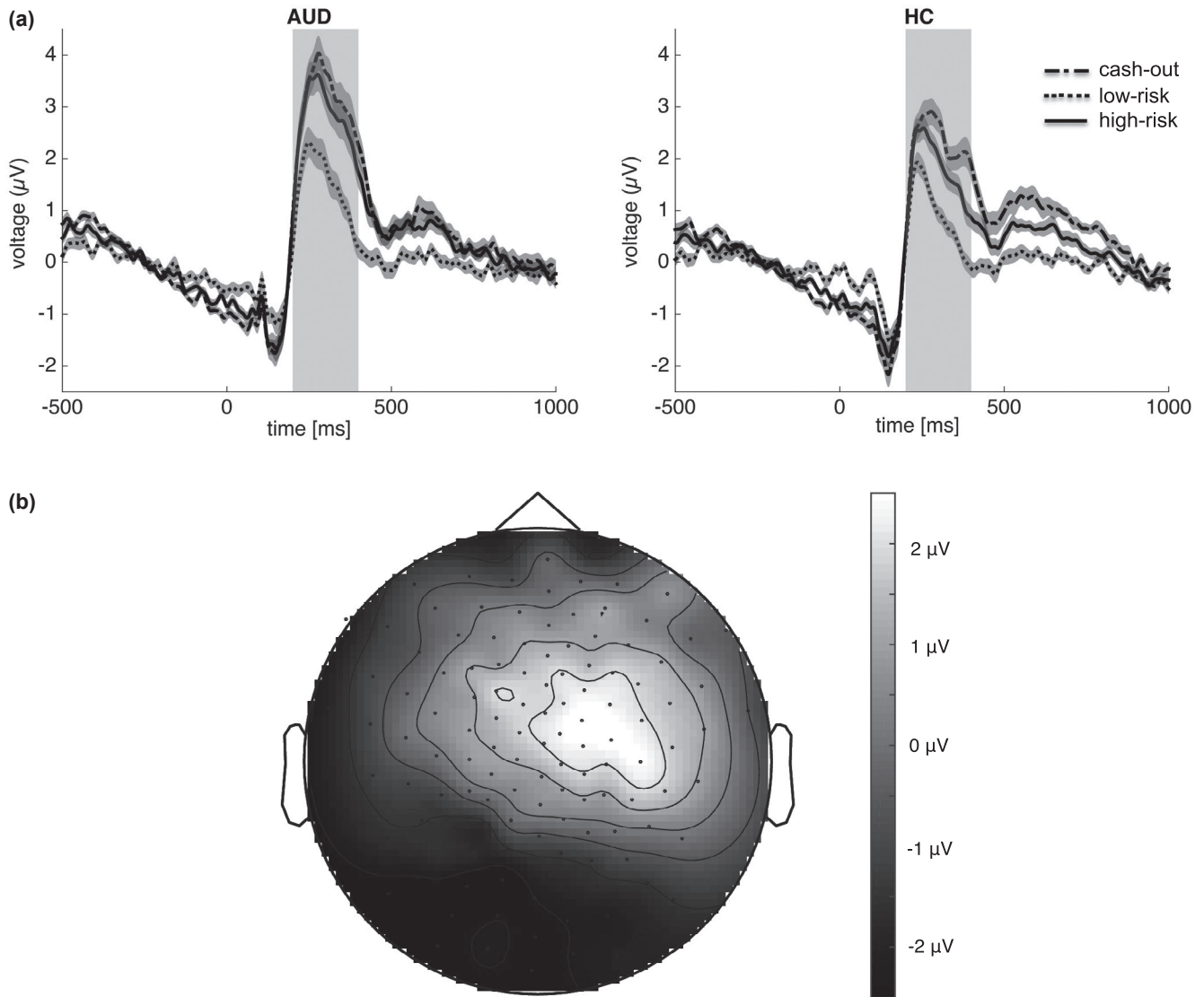


FIGURE 2 (a) ERP waveforms time-locked to the onset of the decision prompt at 0 ms relative to 500 ms prestimulus baseline, averaged over 13 central-parietal electrodes separately by group (AUD: patients with alcohol use disorder; HC: healthy controls) and risk. Gray bar indicates the 200–400 ms window during which the positive peak amplitude was scored as decision P3. (b) Topo map of decision P3 on high- minus low-risk trials across all subjects

3.3 | Outcome evaluation

3.3.1 | Feedback-related negativity

Figure 3 illustrates ERP waveforms at frontal electrodes time-locked to the onset of feedback. In support of Hypothesis 3, peak-to-peak FRN was larger for loss than for cash-out (outcome, $F(1, 72) = 192.65, p < .001, \eta_p^2 = .73$). In further support of Hypothesis 3, the enhancement of FRN for loss compared to cash-out feedback was more prominent in HC than in AUD (group, $F(1, 72) = 2.78, p = .100, \eta_p^2 = .04$; Group \times Outcome, $F(1, 72) = 6.90, p = .011, \eta_p^2 = .09$). Groups differed in FRN after loss feedback, $F(1, 72) = 4.96, p = .029, \eta_p^2 = .06$, but not after cash-out feedback, $F(1, 72) = 1.73, p = .193, \eta_p^2 = .02$. Impulsivity as

a covariate had no impact on FRN (impulsivity, $F(1, 70) = .59, p = .447, \eta_p^2 = .01$; Impulsivity \times Outcome, $F(1, 70) = 2.53, p = .116, \eta_p^2 = .04$) and did not change the impact of group and outcome on FRN reported above (outcome, $F(1, 70) = 6.07, p = .016, \eta_p^2 = .08$; group $F(1, 70) = 3.70, p = .058, \eta_p^2 = .05$; Group \times Outcome, $F(1, 70) = 10.09, p = .002, \eta_p^2 = .13$).

3.3.2 | Reward positivity

Figure 4 illustrates the difference wave of win minus loss trials (see Method above) from which RewP was scored. The group difference in RewP fell short of significance (group, $F(1, 72) = 2.65, p = .108, \eta_p^2 = .04$). However, post hoc analyses of win ERP referred to baseline suggest that this result

TABLE 4 Decision P3 simple-effects ANOVA and pairwise comparisons

	AUD, <i>M</i> (<i>SD</i>)	HC, <i>M</i> (<i>SD</i>)	<i>F</i>	Effect size
Cash-out	5.13 (2.20)	3.93 (1.43)	7.53*	.10
Low-risk	3.20 (1.84)	2.43 (1.06)	4.76*	.06
High-risk	4.71 (2.04)	3.38 (1.25)	11.15**	.13
Cash-out vs. low-risk			79.29**	.52
Low-risk vs. high risk			64.12**	.47
High-risk vs. cash-out			11.79**	.14

Note: Mean and *SD* in microvolts from prestimulus baseline. Effect size = partial η^2 .

Abbreviations: AUD, patients with alcohol use disorders; HC, healthy comparison participants; *M*, mean; *SD*, standard deviation.

* $p < .05$; ** $p \leq .001$.

may be a consequence of smaller FRN upon loss in AUD than in HC (as already reported in the preceding paragraph for FRN, $F(1, 72) = 4.96, p = 0.029$) and a positive frontal deflection upon win feedback (labeled P2a by Potts, Martin, Burton, & Montague, 2006), which was larger in AUD than in HC (group, $F(1, 72) = 8.411, p = .005, \eta_p^2 = .11$). It should be noted, however, that this frontal P2 may overlap with decision P3. Impulsivity as a covariate had no impact on RewP (impulsivity, $F(1, 70) = .714, p = .401, \eta_p^2 = .01$) and did not modify the group difference in RewP reported above (group, $F(1, 70) = 3.36, p = .071$; Group \times Impulsivity, $F(1, 70) = 1.92, p = .155, \eta_p^2 = .05$). As expected, impulsivity was associated with the P2 on win trials ($r = .315, p = .007$).

3.3.3 | Feedback P3

Figure 5 illustrates ERP waveforms at central-parietal electrodes time-locked to the onset of the feedback. Per Hypothesis 3, feedback P3 was larger for loss than for cash-out feedback (outcome, $F(1, 72) = 248.84, p < .001, \eta_p^2 = .78$). Contrary to Hypothesis 3, groups did not differ in feedback P3 overall (group, $F(1, 72) = .18, p = .671, \eta_p^2 = .00$) or as a function of outcome (Group \times Outcome, $F(1, 72) = .47, p = .494, \eta_p^2 = .01$). Impulsivity as a covariate had no impact on feedback P3 (impulsivity, $F(1, 70) = 2.14, p = .147, \eta_p^2 = .03$; Impulsivity \times Outcome, $F(1, 70) = 2.45, p = .122, \eta_p^2 = .03$) and did not change the relationships reported above (outcome, $F(1, 70) = 9.21, p = .003, \eta_p^2 = .12$); group, $F(1, 70) = 1.42, p = .238, \eta_p^2 = .02$; Group \times Outcome, $F(1, 70) = 2.17, p = .145, \eta_p^2 = .03$).

3.4 | Performance prediction

Addressing Hypothesis 4, the full regression model with group, impulsivity, decision P3 difference between high-risk and low-risk trials, and Group \times Decision P3 difference

interaction as predictors accounted for 13% of the variance in number of pumps, $F(4, 68) = 2.61, p = .043$; Table 5. Neither group nor impulsivity contributed variance (each $\Delta R^2 = .00$),⁶ whereas decision P3 difference predicted the number of pumps ($\Delta R^2 = .09, p = .010$). The Group \times Decision P3 difference interaction contributed marginally ($\Delta R^2 = .04, p = .083$). Because Hypothesis 4 was directional, justifying a one-tailed test, this interaction can be considered statistically reliable. Accordingly, follow-up analyses confirmed that the decision P3 difference predicted number of pumps only in AUD ($R^2 = .23, F(1, 37) = 10.80, p = .002$): larger differences between high-risk trials and low-risk trials predicted more risky choices. No relationship was found for HC ($R^2 = .00$).

The same hierarchical regression was undertaken to predict RT. Group, impulsivity, decision P3 difference, and Group \times Decision P3 difference interaction together accounted for a considerable 20% of the variance in RT, $F(4, 68) = 4.28, p = .004$. Group alone provided much of that ($R^2 = .12, p = .003$),⁷ indicating that AUD responded more slowly than HC, whereas impulsivity did not contribute unique variance ($\Delta R^2 = .00, p = .864$). Larger decision P3 differences were associated with faster responses ($\Delta R^2 = .06, p = .027$), whereas the Group \times Decision P3 difference interaction did not improve prediction ($\Delta R^2 = .02, p = .157$). Parallel regression analyses for FRN upon loss identified only group as a significant predictor ($R^2 = .07, F(1, 71) = 5.68, p = .020$).

4 | DISCUSSION

The incongruity between ongoing harmful drinking behavior and knowledge of risks and/or experience of negative

⁶This regression test is redundant with the ANOVA test in the first row of Table 2.

⁷This regression test is redundant with the ANOVA test in the first row of Table 3.

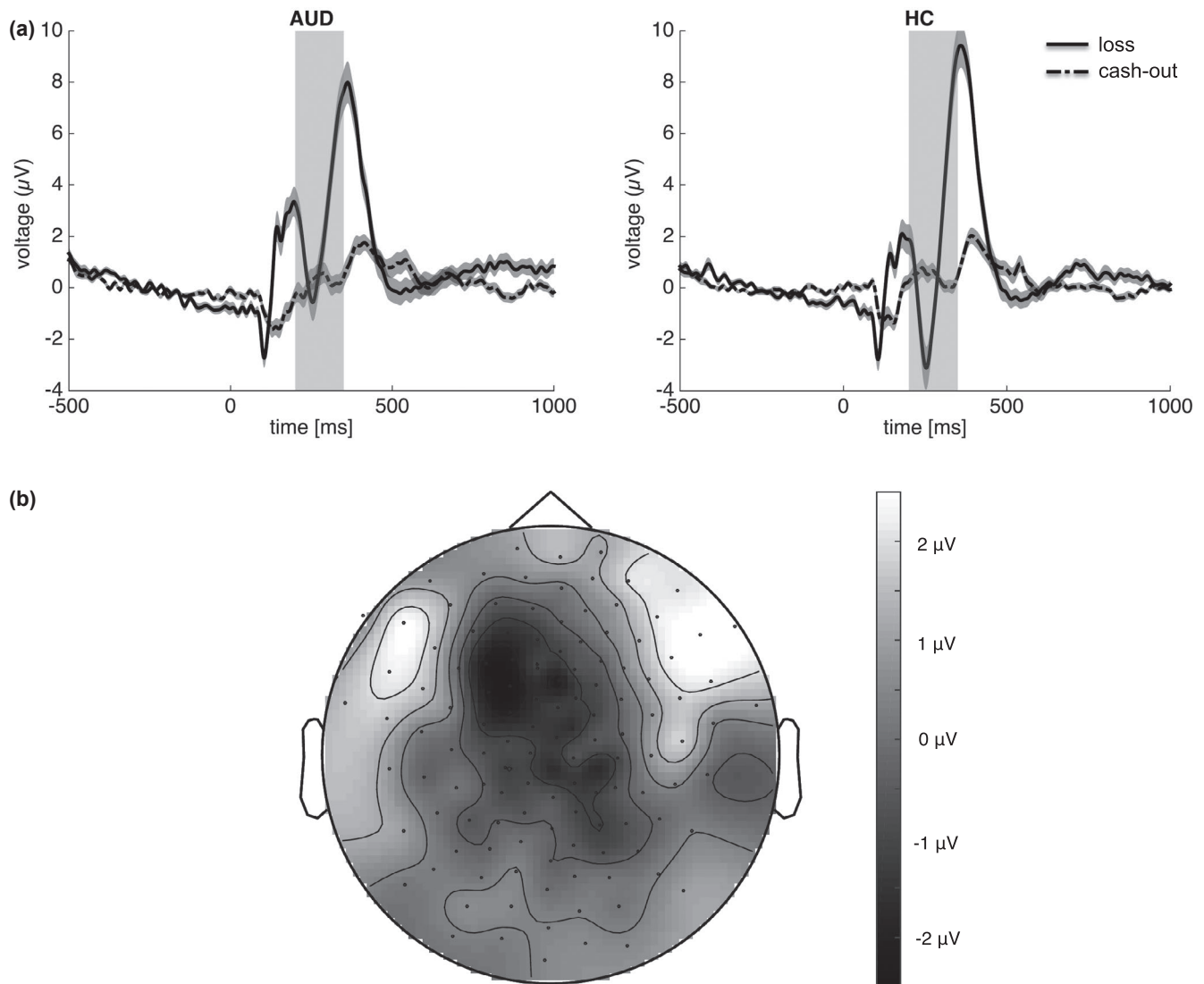


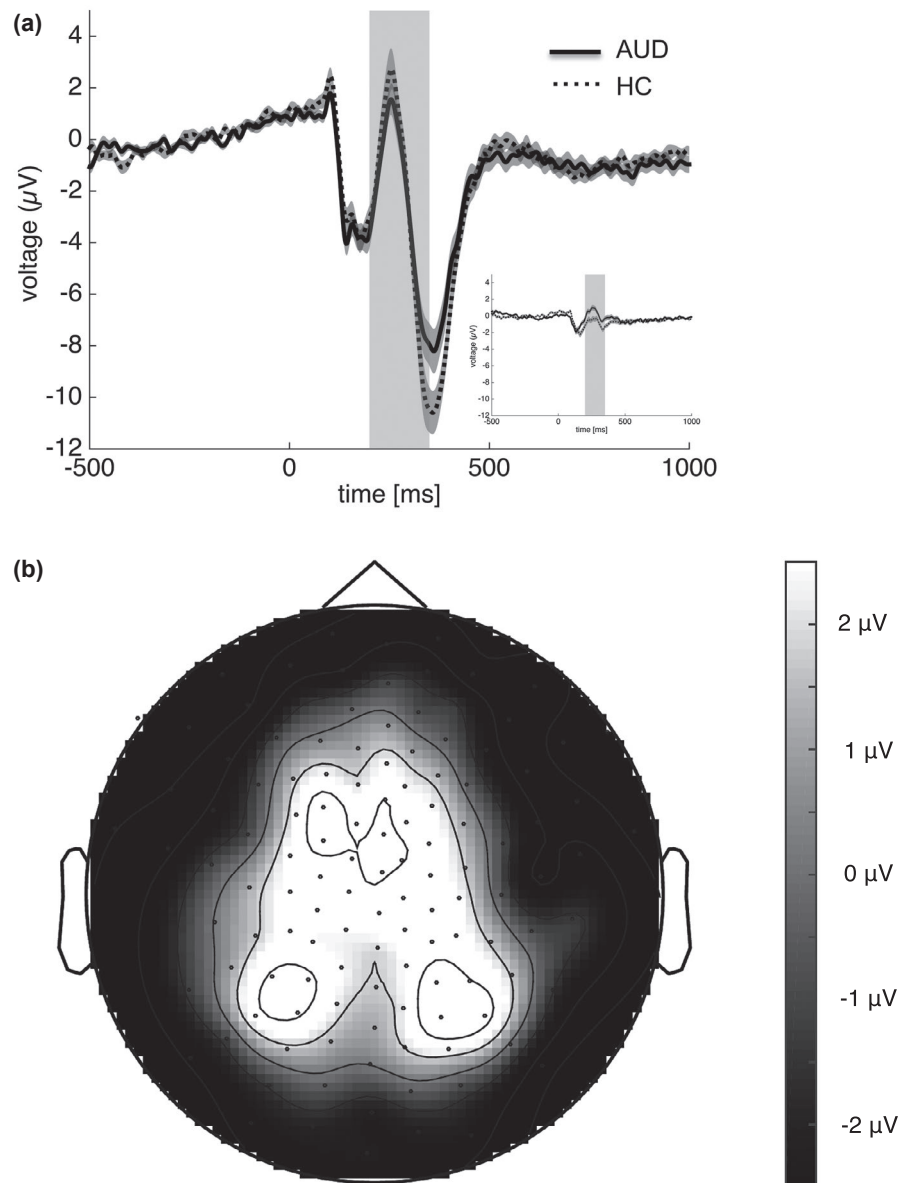
FIGURE 3 (a) ERP waveforms time-locked to the onset of the outcome feedback at 0 ms relative to 500 ms prestimulus baseline, averaged over 5 frontal electrodes by group (AUD: patients with alcohol use disorder; HC: healthy controls) and outcome condition. Gray bar indicates the 200–350 ms window during which the negative peak amplitude was scored as feedback-related negativity (FRN). (b) Topo map of FRN on loss minus cash-out trials across all subjects

physical, psychological, social, and economic consequences of alcohol abuse is not well understood. The present study sought to identify and distinguish the contributions of decision-related versus feedback-related processes to problematic decision making in AUD by adapting a commonly used task to evaluate both processes. AUD and HC showed similar overt choice behavior but differed in both decision- and feedback-related ERPs: AUD exhibited larger decision P3 (independent of risk level) yet showed diminished FRN enhancement, suggesting poor responsiveness to loss feedback. In addition, higher responsiveness to successful decisions (signaling win) supports the hypothesis of dysfunctional feedback processing in AUD.

This pattern of results identifies distinct anomalies at decision- and feedback-evaluation stages. Most fundamentally, the large decision P3 (Cuzen, Andrew, Thomas,

Stein, & Fein, 2013; Lopez-Caneda et al., 2013) and its normal variation as a function of decision choice (Euser, Greaves-Lord et al., 2013; Gu et al., 2018; Steffen et al., 2011) argue that poor decision behavior in AUD is not a function of failing to engage decision prompts but is, at least in part, a subsequent failure to process differential feedback. The decision P3 (or N2-P3 complex) has been related to reward prediction (Hajcak et al., 2005; Steffen et al., 2011; Yeung & Sanfey, 2004) and to more effortful processing supported by the recruitment of additional neural or cognitive resources for difficult choices (Kiefer, Marzinzik, Weisbrod, Scherg, & Spitzer, 1998; Lopez-Caneda et al., 2012; Petit et al., 2014; Sirevaag, Kramer, Coles, & Donchin, 1989; Yee & Miller, 1994). As part of the N2-P3 complex, the larger decision P3 in AUD may thus reflect more intense processing of the decision prompt

FIGURE 4 (a) Difference wave of ERP waveforms of win feedback (picture of the next larger balloon signaling a successful pump) minus loss feedback (popped balloon) at 0 ms relative to 500 ms prestimulus baseline, averaged over 5 frontal electrodes by group (AUD: patients with alcohol use disorder, HC: healthy controls) and risk. Gray bar indicates the 200–350 ms window during which the positive peak amplitude of the difference wave was scored as reward positivity (RewP). Inset displays ERP waveforms of win feedback (brain potentials of loss feedback are illustrated in Figure 3a). (b) Topo map of RewP on win minus loss trials across all subjects



with respect to learning-based outcome expectancies and valuation, in combination guiding top-down control of decision choice supported by anterior cingulate activity (Holroyd & Yeung, 2012). However, interpretation of the present decision P3 must remain hypothetical, because the sequential decision design does not allow a clear distinction between the different processes that may have been activated by the decision prompt. The timing of the prediction of the chance of winning probably overlaps with updating of decision risk and reinforcement contingency from the previous decisions. It may be concluded that these processes were more activated in AUD than in HC in the present design without specifying the dominance or priority of the potentially involved decision-guiding process.

The common finding of higher FRN amplitudes following loss than reward (Gehring & Willoughby, 2002; Holroyd & Coles, 2002; Sambrook & Goslin, 2015) was confirmed

for both groups but was smaller in AUD than in HC. This smaller FRN after loss in AUD suggests a critical failure to benefit from judgment errors. FRN has been associated with the matching of actual outcomes with expectations (reward prediction errors; Holroyd & Coles, 2002; Sambrook & Goslin, 2015), the comparison of outcome valence, and/or the violation of outcome expectations (Fishman, Goldman, & Donchin, 2008). An attenuated FRN may thus reflect impaired prediction error judgment in AUD, which has been suggested for addicted populations (e.g., Baker, Stockwell, et al., 2016; Parvaz et al., 2015). Blunted FRN amplitudes have been related to less self-reported sensitivity to punishment (Santesso, Dzyundzyak, & Segalowitz, 2011) and less negative affect after loss feedback (Santesso, Bogdan et al., 2011). This pattern would make sense in view of dysfunctional and dampened ACC activity in addicted populations (Volkow, Wang, Fowler, Tomasi, & Telang, 2011). As this

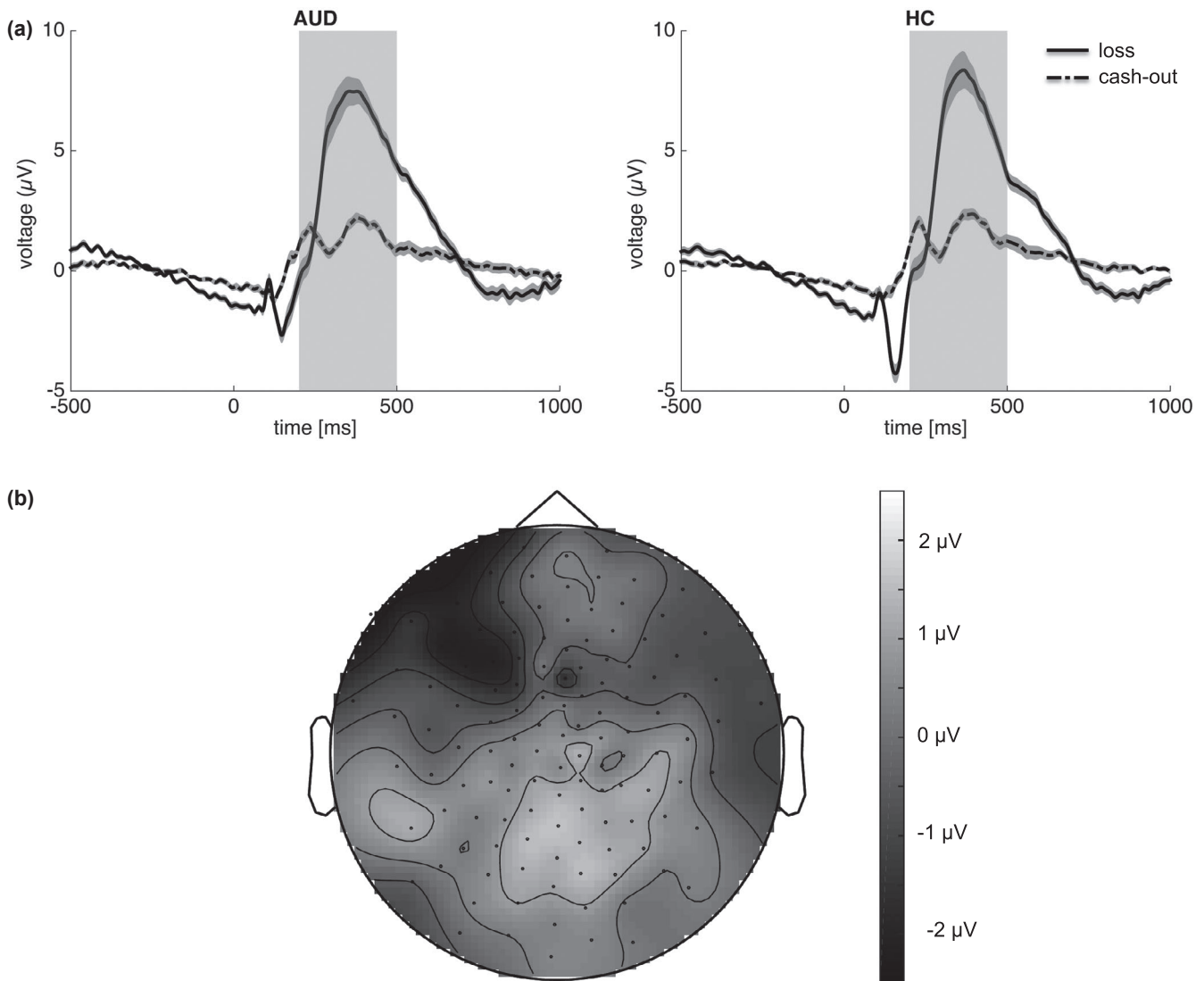


FIGURE 5 (a) ERP waveforms time-locked to the onset of the outcome feedback at 0 ms relative to 500 ms prestimulus baseline, averaged over 13 central-parietal electrodes separately by group (AUD: patients with alcohol use disorder; HC: healthy controls) and outcome condition. Gray bar indicates the 200–500 ms window during which the positive peak amplitude was scored as feedback P3. (b) Topo map of feedback P3 on loss minus cash-out trials across all subjects

TABLE 5 Number of pumps hierarchical regression analysis

	R^2	ΔR^2	T
Step 1: Group	.00	.00	0.09
Step 2: Impulsivity	.00	.00	-0.11
Step 3: Decision P3 difference	.08	.08	2.66*
Step 4: Group \times Decision P3 difference	.13	.04	-1.76 ⁺

Note: R^2 values are the total variance explained by all predictors in the model at that step. ΔR^2 values are the increase in variance explained by the predictor added to the model at that step.

⁺ $p < .1$; * $p < .05$.

indifference to loss feedback was evident in the context of decisions and rewards unrelated to alcohol use, present FRN

results are consistent with a potentially broad deficit affecting diverse life contexts.

Operationalized as response difference between win and loss outcomes, the RewP did not significantly differ between AUD and HC. However, closer inspection and post hoc analyses point to two deviations in AUD responses to win and loss feedback from those in HC, which, because they are opposite in direction, a difference wave may not reveal: a tendency for larger response upon win feedback and a tendency for smaller FRN upon loss feedback in AUD than in HC. Of note, when risky decisions to continue pumping were rewarded by seeing the next-sized balloon (win feedback), AUD exhibited larger frontal positivity than HC after approximately 200–350 ms (referred to here as the P2a, see Potts et al., 2006). The P2a after unpredicted

reward has been related to the mesotelencephalic dopamine system and interpreted as an index of attention selection and salience evaluation (Potts et al., 2006; Soder & Potts, 2018). In the present AUD sample, the accentuated P2a might indicate heightened motivational significance of rewarding stimuli in AUD, which may foster continued alcohol use despite negative consequences. The smaller FRN to loss outcome in AUD is particularly interesting in combination with the larger P2a to win feedback. While keeping in mind the slight difference in type of feedback (the next-sized balloon in a series of decisions reinforces the decision to take the risk, whereas balloon popping means loss of the run's gain), the combination of accentuated salience evaluation and dampened response to failure may promote behavioral orientation toward reward in AUD, reinforcing the continuation of risky alcohol use despite negative consequences. Dysfunctional ACC activity reported in AUD (Baker, Stockwell et al., 2016; Baker, Wood et al., 2016; Parvaz et al., 2015; Volkow et al., 2011) offers a framework for such hypotheses.

It should be noted that the interpretation of present P2 and/or RewP results is speculative, because the sequential decision task, in which the same stimulus may have two meanings, does not allow a clear distinction between ERP components reflecting reward prediction, reward feedback, and decision choice ("go"). The frontal P2a emerging from the comparison of positive and negative feedback (win minus loss) may overlap with the central P3 emerging from the comparison of riskier and less risky decisions.

That impulsivity may moderate present results is noted in the Introduction. Impulsivity is considered a prominent feature of AUD (Dick et al., 2010; Kumar et al., 2018) and is associated with higher reward sensitivity and deficits in behavioral inhibition (Rossiter, Thompson, & Hester, 2012). As expected, impulsivity was highly correlated with AUD in the present study. As a consequence, group effects on decision P3 were diminished when impulsivity was added as a covariate. This redundancy indicates that, for the most part, neither AUD status nor impulsivity contributed unique variance in the present decision context. Impulsivity might also lower response thresholds and facilitate activity of a "go system" (Marinkovic, Halgren, Klopp, & Maltzman, 2000), here indicated by the prominent decision P3 in AUD.

The Group \times Outcome effect on FRN survived addition of impulsivity as a covariate (in fact grew slightly, from $\eta_p^2 = .09$ to $\eta_p^2 = .13$). This finding should be interpreted with caution but suggests that there is more to AUD than impulsivity, which of course is reflected in diagnostic criteria for AUD. Further research on factors explaining altered risk taking and altered processing in AUD could involve consideration of other personality and psychopathology risk factors (e.g., internalizing psychopathology such as depression; Foti et al., 2014).

A relationship between decision P3 as an index of reward prediction and FRN as an index of the comparison between expectation and outcome was not established. Independence of decision- and outcome-related processes might indicate that risk-taking propensity is unaffected by feedback. Such indifference to outcome feedback would undermine adaptive decision behavior guided by balancing risks of potential negative and positive consequences (Brown et al., 2015). Present analyses cannot adequately test this hypothesis. It is conceivable that the relationship between decision- and feedback-related ERP components varies from decision to decision, with disappointment (loss) affecting reward prediction (decision P3) and choice on the subsequent trial. Thus, sequential cross-trial analyses of ERP relationships would be of interest. Mitigating the high single-trial variability of ERP components would likely require far more trials than were available here. A further challenge to disentangling decision- and feedback-related processes in the BART is that they overlap, in that appearance of the next-sized balloon represents a decision prompt as well as feedback about a successful (prior) decision.

Several less critical aspects of present findings warrant comment. AUD were generally slower to respond than HC, and AUD had fewer years of education. Education added as a covariate did not modify findings for decision behavior and ERP components, but an impact of cognitive impairment, which was not systematically assessed and may overlap with or interact with education and with excessive alcohol consumption, on general slowing cannot be ruled out.

That AUD did not make riskier choices than HC is in contrast to reports of enhanced risk propensity in AUD or problem drinkers but in agreement with reports of normal choice behavior (Moallem & Ray, 2012) or even more risk-averse decisions in the BART (Ashenhurst, Bujarski, Jentsch, & Ray, 2014; Ashenhurst, Jentsch, & Ray, 2011). Contrary to present expectation, impulsivity did not affect choice behavior. The present lack of performance differences between AUD and HC and the lack of influence of impulsivity on performance may have resulted from the present BART variant, which included a larger number of runs with fewer balloon sizes than the original BART, in order to facilitate ERP analysis. This variant (following Helfinstein et al., 2014) may have restricted overt response variability and may have fostered overlap of response distributions of the two samples. It is also conceivable that experimental tasks with decision prompts unrelated to alcohol and anticipation of limited monetary reward were not engaging enough to reveal augmented risk propensity in AUD. Using alcohol-related words as decision prompts has been found to interrupt inhibitory control in AUD, increasing commission errors and decreasing reaction time (Kreusch, Billieux, & Quertemont, 2017). More commission errors together with augmented P3 reactivity to alcohol-related cues have also been reported in heavy social

drinkers (Petit, Kornreich, Noël, Verbanck, & Campanella, 2012) and in binge drinkers (Petit, Kornreich, Verbanck, & Campanella, 2013).

Group differences in outcome-related measures were limited to FRN. Both groups displayed larger feedback P3 to loss (disappointing expectation) than to cash-out (confirming expectation) feedback. The lack of group difference was not an issue of power, as group and Group \times Outcome F s were much less than 1.00. Inconsistent interpretations of the feedback P3 preclude confident conclusions. Whereas Euser et al. (2011) associated both FRN and feedback P3 with outcome evaluation and found both components to be altered in AUD, Padrón and colleagues distinguished FRN as sensitive to outcome valence from feedback P3 as affected by outcome magnitude: “FRN and the feedback P300 in fact reflect different performance monitoring processes in a flexible way that depends on the behavioral context” (Padrón, Fernández-Rey, Acuña, & Pardo-Vazquez, 2016, p. 264). Smaller FRN in present AUD may have reflected less sensitivity to “primary or salient stimulus attributes (often gain vs. loss) ...” (Bernat, Nelson, & Baskin-Sommers, 2015, p. 1), whereas outcome magnitude in the present task was less relevant, explaining the similar feedback P3 in AUD and HC.

Hypothesis 4 proposed a relation between the decision P3 and overt decision behavior in HC, less so in AUD patients. Results were contrary, with a significant association between larger decision P3 and riskier choices in AUD, not in HC. The larger decision P3 in AUD may reflect the impact of effortful go decisions. Specifically, risk-inclined AUD producing both larger decision P3 and longer RT on high-risk trials suggests considerable decision-making effort, rather than simply high impulsiveness.

In sum, the present evaluation of decision-related and feedback-related ERP components in AUD points to appropriate risk evaluation, though with more effort invested in processing, whereas altered feedback processing may reflect reward approach and penalty avoidance as contributions to risky alcohol use despite knowledge of negative consequences. In light of the challenges and limitations of ERP analyses in the BART, these conclusions warrant further substantiation.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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