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FULL-LENGTH REPORT

# Gambling disorder is associated with reduced sensitivity to expected value during risky choice

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**ABSTRACT**

*Background and aims:* Individuals with gambling disorder display increased levels of risk-taking, but it is not known if it is associated with an altered subjective valuation of gains and/or losses, perception of their probabilities, or integration of these sources of information into expected value. *Methods:* Participants with gambling disorder ($n = 48$) were compared with a healthy comparison group ($n = 35$) on a two-choice lottery task that involved either gains-only or losses-only gambles. On each trial, two lotteries were displayed, showing the associated probability and magnitude of the possible outcome for each. On each trial, participants chose one of the two lotteries, and the outcome was revealed. *Results:* Choice behaviour was highly sensitive to the expected value of the two gambles in both the gain and loss domains. This sensitivity to expected value was attenuated in the group with gambling disorder. The group with gambling disorder used both probability and magnitude information less, and this impairment was greater for probability information. By contrast, they used prior feedback (win vs loss) to inform their next choice, despite the independence of each trial. Within the gambling disorder group, problem gambling severity and trait gambling-related cognitions independently predicted reduced sensitivity to expected value. The majority of observed effects were consistent across both gain and loss domains. *Discussion and Conclusions:* Our results provide a thorough characterization of decision processes in gain and loss domains in gambling disorder, and place these problems in the context of theoretical constructs from behavioural economics.

**KEYWORDS**

decision-making, expected value, gambling disorder, gambling

## INTRODUCTION

Gambling disorder, classified as a behavioural addiction in the DSM-5 and ICD-11, is associated with continued gambling in the face of mounting losses, often at the detriment of financial, social, and occupational obligations (Grant & Chamberlain, 2016; Hodgins, Stea, & Grant, 2011). All forms of gambling entail integrating information about the probability and magnitude of rewards in order to decide whether and how much to gamble. This information may be explicit (e.g. roulette) or ambiguous (e.g. slot machines) reminiscent of the classic

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economic distinction between choice under explicit risk versus uncertainty (De Groot & Thurik, 2018; Knight, 1921). All forms of modern, commercial gambling are characterized by a negative expected value (EV) (or 'house edge'), formalized as the product term of the outcome probability and magnitude. A central psychological paradox of gambling behaviour is why the widespread recognition among gamblers that "the house always wins" does not prevent excessive gambling in individuals with gambling disorder.

Prior work using laboratory tasks to investigate decision-making under risk, where probability and magnitude are explicit, has fallen into two camps; studies that categorise decisions as safe or risky and count the proportion of risky decisions, and those that have attempted to model what is driving decision making using constructs from behavioural economics (Schonberg, Fox, & Poldrack, 2011). The first has found that groups with disordered gambling make suboptimal (i.e. lower EV) and risky choices, in tasks such as the Game of Dice task (Brand et al., 2005; Brevers et al., 2012) and cups task (Brevers et al., 2012; Buchanan, McMullin, Mulhauser, Weinstock, & Weller, 2020). In the Cambridge Gamble Task, where participants choose between two probabilities, and are therefore not required to integrate magnitude information, participants with gambling disorder also make more suboptimal choices (Limbrick-Oldfield et al., 2020; Zois et al., 2014), but this has not been consistently observed (Lawrence, Luty, Bogdan, Sahakian, & Clark, 2009; Wilson & Vassileva, 2018).

The second approach has investigated decision-making under risk from the lens of behavioural economics, in an attempt to elucidate whether the suboptimal decision-making in gambling disorder is associated with changes in subjective weighting of probabilities (Ligneul, Sescousse, Barbalat, Domenech, & Dreher, 2012; Ring et al., 2018) or in the shape of the 'value function' that maps objective to subjective value. For example, loss aversion (the overweighting of losses compared to equivalent-size gains) was seen to be reduced in gambling disorder in some but not all studies (Gelskov, Madsen, Ramsøy, & Siebner, 2016; Genauck et al., 2017; Giorgetta et al., 2014; Takeuchi et al., 2015).

Much of the research investigating risky decision-making in gambling disorder has employed mixed gambles (i.e. choices that include both gain and loss outcomes), which does not allow disambiguation of gain- and loss-related differences. Other studies, particularly using neuroimaging, have focused on appetitive processing (Clark, Boileau, & Zack, 2019; Comings & Blum, 2000; Robinson & Berridge, 2008). Aversive processing has received less attention, despite the recognition that altered processing of loss and negative consequences could contribute to gambling disorder (Brunborg et al., 2012). In a loss only version of the cups task, individuals with gambling disorder did not show suboptimal decision-making (Brevers et al., 2012) and a more recent loss task did not observe any differences in the use of probability information in gambling disorder (Ring et al., 2018).

Gamblers' choices in these two domains may also be differentially affected by prior feedback. On the Iowa Gambling Task, which requires learning from preceding trial outcomes, individuals with gambling disorder switched their choice behaviour less as a function of preceding feedback compared to controls (Goudriaan, Oosterlaan, de Beurs, & Van Den Brink, 2005). In regular gamblers, higher problem gambling scores were associated with reduced use of reinforcement history in a reinforcement learning task (Lim, Jocham, Hunt, Behrens, & Rogers, 2015). However, in decision-making under risk, where all information is presented and no learning is required, previous feedback does not provide information about the current trial. Here gamblers show the reverse bias, and use previous feedback information when placing bets on roulette (Croson & Sundali, 2005; Goudriaan et al., 2005). Prior work has not characterized the use of such feedback information in gambling disorder.

Here we investigate two main aspects of decision-making under risk that have not been investigated previously in gambling disorder. First, rather than simply count the number of suboptimal decisions, we investigate the use of relevant EV information in both a gain- and loss-only context, and second, we investigate the use of preceding feedback in decision-making under risk. We measure decision-making in gambling disorder and a healthy control group using a task that entails a series of choices between two gambles. The Vancouver Gambling Task (VGT) (Sharp, Viswanathan, Lanyon, & Barton, 2012; Sharp, Viswanathan, McKeown, et al., 2013) is well-suited for examining EV, as it elicits choices spanning a range of relative EVs. Because both prospects are uncertain, optimal decisions on the task require integrating EVs across the two gambles. We administered two versions of the VGT to evaluate decision-making in the context of gains and losses. Prior work on the task shows that across both versions, the choices of healthy participants are driven by the relative EV of the two options (Cherkasova et al., 2018; Sharp, Viswanathan, et al., 2012; Sharp, Viswanathan, McKeown, et al., 2013), albeit with further biases that reflect the prioritization of probability over magnitude information.

We hypothesized that individuals with gambling disorder would show impaired use of EV information, as indicated by a choice function that was less sensitive to the EV ratio of the two gambles, compared to the healthy comparison group. We had no *a priori* prediction as to whether this would be due to altered processing of probability information, magnitude information, or preceding feedback. We predicted that group differences would be present in both gain and loss conditions, but we tested for any asymmetry (Brevers et al., 2012; Ring et al., 2018). Within the group with gambling disorder, we further expected that the sensitivity to EV information would be correlated with increasing problem gambling severity and increasing levels of gambling-related cognitive distortions.

## MATERIALS AND METHODS

### Participants

Individuals with gambling disorder ($n$ = 50) were recruited through: (a) online advertisements ($n$ = 41), including Craigslist and Kijiji (online community noticeboards), the

University's online paid studies list, or individuals who directly contacted the laboratory website disclosing gambling problems, or (b) local gambling treatment groups run by the provincial problem gambling program ($n$ = 9). Of the overall group, 32 had never sought treatment for gambling problems, 15 were currently engaged with gambling treatment services, and 3 had completed or discontinued treatment. At the end of test sessions, gambling disorder participants who were not in treatment were given information on local resources for problem gambling. Two gambling disorder participants were excluded from analysis due to failure to complete one or both versions of the VGT, so that data are presented from 48 participants with gambling disorder. The healthy comparison group ($n$ = 38; henceforth, controls) were recruited by advertisements. Three participants were excluded as they did not meet the inclusion criteria, so that data are presented from 35 controls. Controls endorsed no DSM-5 criteria and scored ≤2 on the PGSI, indicating non-problem or low-risk gambling (26 scored 0, 9 scored 1–2). All participants were aged 19–65 years, in good physical health, able to read and understand fluent English, had normal or corrected-to normal eyesight and hearing, no history of head injury or neurological illness, no previous psychiatric hospitalization, and no change in psychiatric medication within the past six weeks.

## Measures

Diagnostic status was confirmed using the pathological gambling section of the Structured Clinical Interview for DSM-IV (First, Spitzer, Gibbon, & Williams, 1997), administered as an interview by a research assistant. The ten DSM-IV criteria were re-coded to the DSM-5 (4 from 9) threshold. Disordered gambling was further corroborated by a score ≥8 on the 9-item Problem Gambling Severity Index (PGSI; (Ferris & Wynne, 2001).

We administered the Depression Anxiety and Stress Scale-21 (Lovibond & Lovibond, 1995) to measure subclinical affective symptoms over the previous week, the Fagerstrom Test for Nicotine Dependence (Heatherton, Kozlowski, Frecker, & Fagerstrom, 1991) to measure smoking severity in participants who smoked, the Alcohol Use Disorders Identification Test (AUDIT) (Bush et al., 1998), the Drug Abuse Screening Test (DAST-10) (Skinner, 1982), and the National Adult Reading Test - Revised (NART-R) (Blair & Spreen, 1989) to estimate verbal IQ. Additional demographics were measured and have been reported previously (Kennedy et al., 2019). Due to a coding error in online questionnaires, item 9 of the DAST-10 was unavailable (hence the maximum score is 9). We administered the Gambling Related Cognitions Scale (GRCS) (Raylu & Oei, 2004), a 23-item scale that assesses trait endorsement of a range of common gambling distortions and gambling expectancies.

## Vancouver gambling task

Decision-making under risk was measured using the VGT (Fig. 1). This is a two-alternative choice lottery task that assesses participants' sensitivity to EV across different combinations of gain/loss magnitudes and probabilities. Participants completed a gains-only version and a losses-only version of the task, with test order counterbalanced within each group. In both versions, one prospect featured a larger but less probable gain (loss) against a zero outcome, whereas the other featured a more probable but smaller gain (loss) against a zero outcome. Participants started the gains-only task with zero coins, and made a series of positive EV choices with the aim of maximising their gains. In the loss version, participants began with 200 coins, and made a series of negative EV choices, with the aim of minimizing their losses. Each trial started with a 500 ms central fixation cross, followed by presentation of a prospect pair. The location (left vs right) of the higher probability option was randomized. Probabilities were represented as pie charts (20 vs. 80%, 30 vs. 70%, 40 vs. 60%) such that the two gambles always displayed different probabilities (and the green sectors in Fig. 1 summed to 100%). Gain (loss) magnitudes were represented using images of coins (1, 2, 3, 4, or 5 coins) below the pie charts. Following the participant's choice, the decision phase was followed by a 1s anticipation phase with a spinning roulette display, followed by the reveal of the gain or loss outcome. See supplemental materials S1 for further details of the task.

## Procedure

Participants were initially assessed for suitability using a telephone interview, before scheduling the 2.5 h laboratory appointment. Following consent, participants completed demographic information, the questionnaire measures, and the psychological tasks, including the VGT. Participants were compensated $30 in gift cards for their participation and were reimbursed for transit/parking costs. A further bonus payment (also paid in gift cards) was given based on their task profits, as financial incentives are important for ecological validity in gambling research (Anderson & Brown, 1984; Ladouceur, Sévigny, Blaszczynski, O'Connor, & Lavoie, 2003). Data from an interoception task collected from the same participants has been published (Kennedy et al., 2019).

## Statistical analysis

Analyses were carried out in R (R Core Team, Vienna), and analysis code is available online (https://github.com/CGR-UBC/VGT_GD_2020). Clinical and demographic characteristics were compared between groups. Choice data from the VGT were analysed using mixed effect logistic regressions, using the lme4 package (Bates, Mächler, Bolker, & Walker, 2014) These models predicted the probability of choosing the high probability, smaller magnitude prospect. Five models were run separately on the gain and loss versions, with a follow-up omnibus model testing the interaction between the two versions (see Table 2 for the predictors of interest of each model, and supplemental tables for a detailed description of each model). Binary predictors of interest were group (controls = 0) and previous feedback (no win or loss = 0). Linear predictors of interest were EV

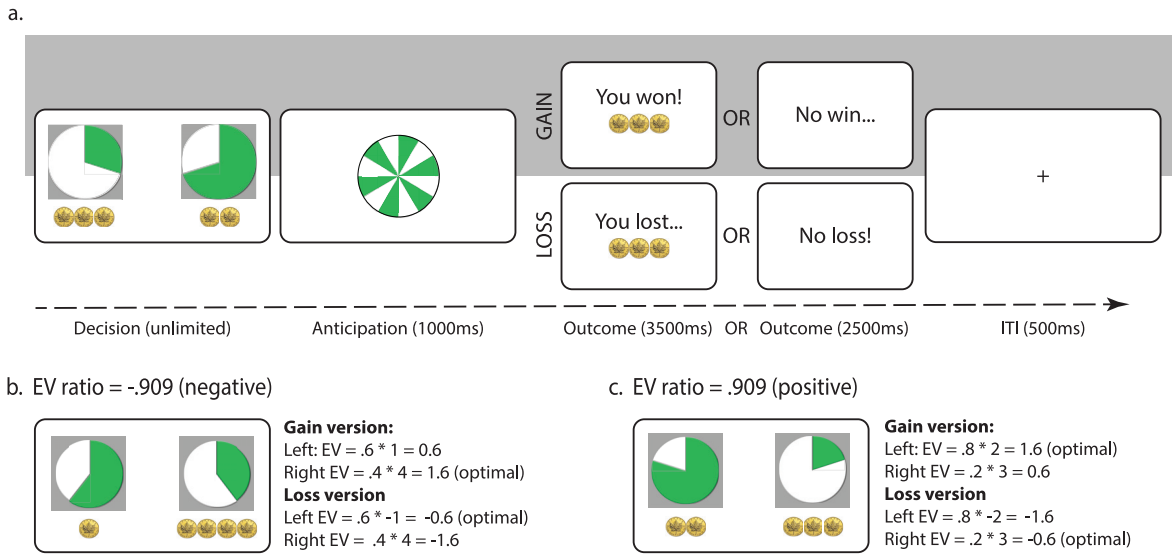


*Fig. 1.* Vancouver Gambling Task. The trial sequence comprised 10 unique gamble pairs (mirrored for the gain and loss versions) that were each repeated 10 times per version (see Table S1). The ten pairs formed a continuum in the relative EVs of the two gambles, ranging from pairs where the higher EV choice was the higher probability, lower magnitude option to pairs where the higher EV choice was the lower probability, higher magnitude option. Each pair was associated with a unique EV difference ratio (referred to for brevity as the EV ratio) calculated as [EV(high P) – EV(low P)]/mean(EV(high P), EV(low P)) as per Sharp et al. (Sharp et al., 2012). a) Example trial sequence showing the gain version (upper, grey background) and the loss version (lower, white background). The probability of winning (losing) is represented by the size of the green segment, whilst the white represents the probability of a zero point outcome. At outcome, gain feedback faded in, whereas loss feedback was portrayed by the coins fading out. b) Example negative EV ratio pair. In the gain version this example trial requires the participant to choose between a prospect with a gain magnitude of 1 at a probability of 0.6 (EV = 0.6, left), or a gain magnitude of 4 at a probability of 0.4 (EV = 1.6, right). At this negative EV ratio the low probability (right) prospect is optimal to maximise gains. In the loss version this example requires the participant to choose between a prospect with a loss magnitude of 1 at a probability of 0.6 (EV = −0.6, left), or a loss magnitude of 4 at a probability of 0.4 (EV = −1.6, right). At this negative EV ratio the high probability (left) prospect is optimal to minimise losses. c) Example positive EV ratio pair. In the gain version this example trial requires the participant to choose between a prospect with a gain magnitude of 2 at a probability of 0.8 (EV = 1.6, left), or a gain magnitude of 3 at a probability of 0.2= (EV = 0.6, right). At this positive EV ratio the high probability (left) prospect is optimal to maximise gains. In the loss version this example requires the participant to choose between a prospect with a loss magnitude of 2 at a probability of 0.8 (EV = −1.6, left), or a loss magnitude of 3 at a probability of 0.2 (EV – 0.6, right). At this negative EV ratio the low probability (right) prospect is optimal to minimise losses. As a larger absolute EV is always optimal for gains, but suboptimal for losses, the optimal choice varies as a function of task version. The position of the high probability prospect was randomized between trials

ratio (zero-centred), clinical variables (mean-centred), probability (mean centred), and magnitude (mean centred). PGSI, GRCS, and the potential confounding clinical variables were only weakly correlated (all $r < 0.23$). We considered the addition of treatment status as an additional regressor, but this variable correlated with PGSI ($r = 0.47$), with those that had sought treatment scoring higher on the PGSI. Results are reported as odds ratios (OR). Nuisance regressors in all models were task version order (loss first = 0) and the prospect pair repetition number (mean-centred). In line with previous work (Cherkasova et al., 2018), the participant term was modelled as a random intercept, and repetition number of the prospect pair as a random slope.

Model assumptions were checked visually, and no violations were identified. The influence of each participant in the model was assessed using the influence.ME package (Nieuwenhuis, te Grotenhuis, & Pelzer, 2012). No participants exerted undue influence in the models.

## Ethics

The study procedures were carried out in accordance with the Declaration of Helsinki. The protocol was approved by the Behavioural Research Ethics Board at the University of British Columbia (H15-00165), and all volunteers were informed about the study and provided written informed consent.

# RESULTS

## Demographics and mental health measures

Of the 48 participants in the gambling disorder group, 23 identified as female and 1 identified as other. Of the 35 participants in the control group, 17 identified as female and 1 identified as other. The groups did not differ significantly on the ratio of male to female participants ($\chi^2(1) = 0$, $P =$

*Table 1.* Demographic and mental health measures, and VGT performance

| | Gambling Disorder | Controls | Statistics |
|---|---|---|---|
| *a. Demographic and mental health measures* | | | |
| *N* | 48 | 35 | ~ |
| Age | 41.5 (22–65) | 32 (21–65) | $U = 663$, $P = 0.10$, $r = 0.18$ |
| DASS | 23 (0–52) | 8 (0–25) | $U = 254.4$, $\mathbf{P < 0.001}$ |
| Estimated Verbal IQ | 93.04 (1.74) | 93.12 (1.19) | $t(63.50) = 0.28$, $P = 0.78$, r = 0.036 |
| AUDIT | 3 (0–12) | 1 (0–8) | $U = 496$, $\mathbf{P < 0.01}$, $r = 0.35$ |
| Past year drug use *n* | 28 (58%) | 7 (19.7%) | $\chi^2(1) = 10.68$, $\mathbf{P < 0.01}$ |
| DAST in drug users | 3 (1–8) | 1 (1–3) | $U = 55$, $P = 0.07$, $r = 0.31$ |
| Smokers *n* | 25 (52%) | 4 (11%) | $\chi^2(1) = 12.98$, $\mathbf{P = < 0.001}$ |
| FTND in smokers | 4 (0–8) | 3.5 (0–5) | $U = 41$, $P = 0.67$, $r = 0.081$ |
| PGSI | 16.5 (8–27) | 0 (0–2) | |
| GRCS | 78.25 (26–142) | 29 (23–161) | $U = 92$, $\mathbf{P < 0.001}$, $r = 0.76$ |
| b. VGT Gain-version | | | |
| Final coin balance | 149.5 (166–195) | 146 (118–177) | *U = 767, P = 0.51, r = 0.073* |
| Chose higher EV prospect | 63% (0–100) | 70% (48–99) | *U = 1,043, P = 0.061, r = 0.205* |
| c. VGT Loss-version | | | |
| Final coin balance | 80 (59–138) | 80 (52–111) | *U = 830, P = 0.93, r = 0.0096* |
| Chose higher EV prospect | 68% (5–100) | 81% (50–100) | *U = 1,009, P = 0.12, r = 0.171* |

*Note.* If data were normal, mean and standard deviation are shown, and unpaired *t*-tests were used to test for group differences. If data violated the assumption of normality, median and range are shown, and Mann-Whitney-U tests were used to test for group differences. Categorical variables were compared using Chi-Square tests. Significant ($P < 0.05$) group differences are highlighted in bold. a. Demographic and clinical characteristics. b. Performance on the gain-version of the VGT. c. Performance on the gain-version of the VGT. AUDIT = alcohol use disorders identification test, DASS = Depression Anxiety Stress Scale, DAST = Drug Abuse Screening Test, FTND = Fagerstrom test for nicotine dependence, GRCS = Gambling related cognitions scale, IQ = intelligence quotient, VGT = Vancouver Gambling Task.

1), age, or verbal IQ (Table 1a). The gambling disorder group showed higher scores on the DASS and AUDIT, and were more likely to smoke tobacco, and use non-medical drugs. However, within smokers, the Fagerstrom severity score did not differ between the two groups, and within the participants who endorsed drug use, the DAST-10 total did not differ between the two groups. The participants with gambling disorder reported slot machines as the most common preferred form of gambling (48%), followed by online gambling (12.5%) and card games (12.5%).

## Gain version

There was no significant group difference in the final coin balance or the percentage of optimum (higher EV) choices (Table 1). For statistical values from the gain version models, see Table 3. Compared to control participants, individuals with gambling disorder used EV ratio information less than controls (Model 1, see Fig. 2a and b). At hypothetical EV = 0, controls were more likely to choose the high probability prospect; this preference was attenuated in the group with gambling disorder (Model 1). The group * EV ratio term remained significant after controlling for potentially confounding clinical variables (AUDIT, DASS, number of smokers, and number who endorsed DAST-10 drug use) (Model 2). In Model 3, the gambling disorder group used both probability and magnitude information less than controls; the gambling disorder group showed a greater insensitivity to the probability information (35.69%, relative to the association in controls) than the magnitude information (21.72%). In controls, EV ratio was not modulated by previous feedback (Model 4, see Fig. 2c). In the gambling disorder group, EV ratio information was used less after a zero-outcome compared to a gain, and this was significantly different from the effect in controls. In the individual differences analyses within the gambling disorder group (Model 5, see Fig. 4a), as gambling severity (PGSI) increased, the relationship between EV ratio and choice was attenuated, and as trait cognitive distortions (GRCS) increased, the relationship between EV ratio and choice was attenuated.

## Loss version

There was no significant group difference in the final coin balance or the percentage of optimum (higher EV) choices (Table 1). For statistical values from the loss version models, see Table 4. Compared to control participants, individuals with gambling disorder used EV ratio information less than controls (Model 1, see Fig. 3a and b). At hypothetical EV = 0, controls were less likely to choose the high probability prospect; this preference was attenuated in the group with gambling disorder (Model 1). However, the group * EV ratio term and the group predictor at hypothetical EV = 0 were not significant after controlling for potentially confounding clinical variables (AUDIT, DASS, number of smokers, and number who endorsed DAST-10 drug use) in Model 2. In Model 3, the gambling disorder group used both probability and magnitude information less than controls; this difference was again greater for the probability information (34.34%, relative to the association in controls) than magnitude (19.71%). In controls, EV ratio was not modulated by previous feedback (Model 4, see Fig. 3c). In the

*Table2.* Predictors of interest in each model of VGT choice behaviour

| Predictors of interest | Research question |
|---|---|
| Model 1. *Group differences in the effect of EV ratio* | |
| EV ratio | Do controls use EV ratio information? |
| EV ratio * group | Do the GD group differ in their sensitivity to EV ratio? |
| Intercept | At hypothetical EV ratio = 0, do controls show a preference for the high or low probability prospect? |
| Group | At hypothetical EV ratio = 0, do the GD group show a different preference to controls? |
| Model 2. *Do potentially confounding clinical variables explain group differences in model 1?* | |
| EV ratio * group | With clinical variables controlled for (clinical variable * EV ratio * group), do the effects of group on EV ratio survive? |
| Group | With clinical variables controlled for, does the group effect at EV = 0 survive? |
| Model 3. *Do the groups differ in their use of probability and magnitude information?*[a] | |
| Probability * group | Do the GD group use probability information more or less than controls? |
| Magnitude * group | Do the GD group use magnitude information more or less than controls? |
| Model 4. *Does previous trial feedback explain choice behaviour?* | |
| EV ratio * Previous feedback | In controls, does the effect of EV ratio differ after a win (or zero outcome) compared to a zero outcome (or loss)? |
| EV ratio * Previous feedback * group | Does the effect of previous trial feedback differ in the GD group compared to controls? |
| EV ratio * Previous feedback (group baseline reversed)[b] | In the GD group, does the effect of EV ratio differ after a win (zero outcome) compared to a zero outcome (loss). |
| Model 5. *Within the GD group, do PGSI or GRCS scores predict the EV ratio effect?* | |
| PGSI * EV ratio | Controlling for other clinical variables in Model 2, does gambling severity predict the EV ratio effect? |
| GRCS * EV ratio | Controlling for other clinical variables in Model 2, do gambling cognitions predict the EV ratio effect? |
| Model 6. *Does EV sensitivity vary as a function of task version (gain or loss)?*[c] | |
| EV ratio * version | In controls, does the effect of EV ratio differ in the gain compared to the loss version? |
| EV ratio * version * group | Does the effect of task version on EV ratio differ in the GD group compared to controls? |

*Note.* The outcome variable was the probability of choosing the high probability prospect. For models 1–5, each model was run separately for the gain and loss version of the task. EV = expected value, GD = gambling disorder, GRCS = gambling related cognitions scale, PGSI = problem gambling severity index.

[a] We performed isometric log ratio transformations on probability and magnitude pairs from each prospect, which yielded a single value representing the prospect pair's probability and a single value representing its magnitude.

[b] To directly observe EV ratio * previous feedback in GD, the baseline was reversed for group, so that GD = 0.

[c] Because we predicted opposite effects of EV ratio on choice in the gain and loss versions, the dependent variable was reversed (probability of choosing the low probability prospect) in the loss version for model 6.

gambling disorder group, EV ratio information was sensitive to previous feedback, being used less after a loss compared to a zero-outcome, but this effect was not significantly different from the effect in controls. In the individual difference analysis within the gambling disorder group (Model 5, see Fig. 4b), the relationship between EV ratio and choice was attenuated as a function of increasing gambling severity (PGSI) and trait cognitive distortions (GRCS).

### Omnibus model (model 6)

In the healthy control group, the relationship between EV ratio and choice was stronger in the gain version of the task than the loss version of the task (EV ratio * version, OR [95% CI] = 1.62 [1.22, 2.14], $P < 0.001$, see Table S8). This effect was not significantly modulated by group (EV ratio * version * group, OR [95% CI] = 0.80 [0.57, 1.13], $P = 0.21$).

## DISCUSSION

Choice behaviour on the VGT followed the relative EV of the two options, albeit with a preference for the high (low) probability prospect in the gain (loss) version. These biases are consistent with previous experiments using this task (Cherkasova et al., 2018; Sharp, Viswanathan, et al., 2012; Sharp, Viswanathan, McKeown, et al., 2013). In individuals

*Table 3.* Results from the predictors of interest in the gain models

| Predictor | OR [95% CI] | *P* value |
|---|---|---|
| Model 1. *Group differences in the effect of EV ratio* (Table S2a) | | |
| Intercept | 6.40 [3.43, 11.95] | <0.001 |
| Group | 0.44 [0.23, 0.86] | <0.05 |
| EV ratio | 26.92 [21.25, 34.10] | <0.001 |
| EV ratio * group | 0.51 [0.38, 0.68] | <0.001 |
| Model 2. *Do potentially confounding clinical variables explain the group differences of model 1?* (Table S3a) | | |
| EV ratio * group | 0.32 [0.17, 0.59] | <0.001 |
| Group | 0.39 [0.12, 1.29] | 0.76 |
| Model 3. *Do the groups differ in their use of probability and magnitude information?* (Table S4a) | | |
| Probability * group | 13.76 [6.12. 30.96] | <0.001 |
| Magnitude * group | 0.42 [0.28, 0.65] | <0.001 |
| Model 4. *Does previous trial feedback also predict choice behaviour?* (Table S5a) | | |
| EV ratio * Previous feedback | 0.71 [0.46, 1.10] | 0.13 |
| EV ratio * Previous feedback * group | 1.93 [1.13, 3.28] | <0.05 |
| EV ratio * Previous feedback (group baseline reversed) | 1.37 [1.01, 1.86] | <0.05 |
| Model 5. *Within the gambling disorder group, do PGSI or GRCS score predict behaviour?* (Table S2a) | | |
| PGSI * EV ratio | 0.89 [0.86, 0.93] | <0.001 |
| GRCS * EV ratio | 0.97 [0.97, 0.98] | <0.001 |

*Note.* Full models reported in supplemental tables. EV = expected value, GRCS = gambling related cognitions scale, PGSI = problem gambling severity index.

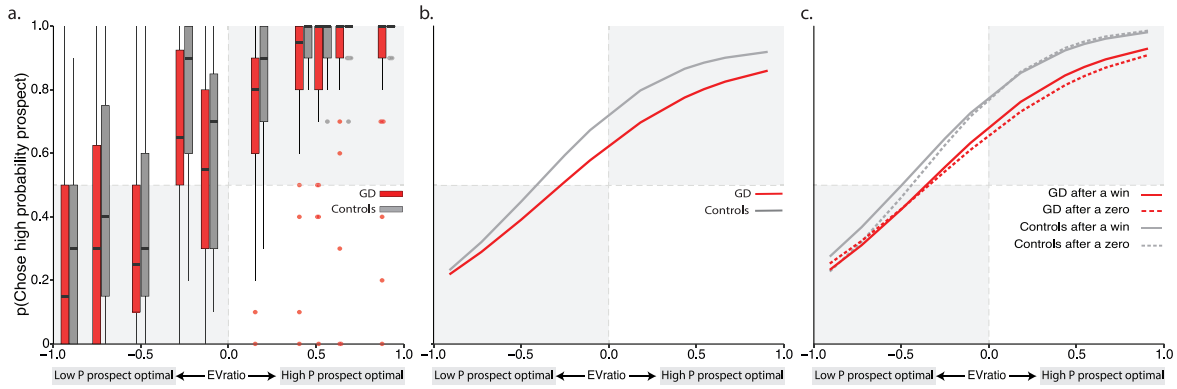


*Fig. 2.* Between group analysis of choice behaviour in the gain version. a) Tukey boxplots of observed behaviour in GD participants and controls. b) Predicted choice behaviour from the logistic regression (Table S2a). Solid line = GD group, dashed line = control group. c) Predicted choice behaviour as a function of previous feedback (Table S5a). Solid lines = choice after a win outcome, dashed lines = choice after a zero outcome. Shaded gray quarters indicate that the low probability prospect is optimal for negative EV ratios, whilst the high probability prospect is optimal for positive EV ratios. Red = GD group, grey = control group. EV, expected value; GD, gambling disorder; P, probability

with gambling disorder, the strength of the relationship between EV ratio and choice was attenuated in both the gain and loss domains, and reflected a dual reduction in sensitivity to both magnitude and probability information. By inference, individuals with gambling disorder may use EV information less when making real-world decisions that rely on integrating probability and magnitude information. Within our gambling disorder group, the relationship between EV ratio and choice was modulated by both problem gambling severity (PGSI) and trait ratings of gambling distortions (GRCS), in a direction that was consistent with the overall group differences. Analyses of decision latency data (see Table S6) did not provide any evidence that the gambling disorder group was simply responding more impulsively (i.e. faster) than controls. Choices in the group with gambling disorder were also sensitive to the feedback from the previous decision; an effect that was not observed in the control group. This is in line with evidence that gamblers are prone to sequential biases including the gambler's fallacy (Croson & Sundali, 2005; Gaissmaier, Wilke, Scheibehenne, McCanney, & Barrett, 2016) when the preceding feedback does not inform the outcome of the current

*Table 4.* Results from the predictors of interest in the loss models

| Predictor | OR [95% CI] | *P* value |
|---|---|---|
| Model 1. *Group differences in the effect of EV ratio* (Table S2b) | | |
| Intercept | 0.12 [0.056, 0.24] | <0.001 |
| Group | 2.41 [1.10, 5.28] | <0.05 |
| EV ratio | 0.052 [0.041, 0.065] | <0.0 01 |
| EV ratio * group | 1.82 [1.37, 2.43] | <0.001 |
| Model 2. *Do potentially confounding clinical variables explain the group differences of model 1?* (Table S3b) | | |
| EV ratio * group | 1.46 [0.82, 2.60] | 0.20 |
| Group | 0.60 [0.15, 2.35] | 0.46 |
| Model 3. *Do the groups differ in their use of probability and magnitude information?* (Table S4b) | | |
| Probability * group | 0.12 [0.052, 0.25] | <0.001 |
| Magnitude * group | 1.99 [1.30, 3.04] | <0.01 |
| Model 4. *Does previous trial feedback also predict choice behaviour?* (Table S5b) | | |
| EV ratio * Previous feedback | 1.25 [0.81, 1.93] | 0.32 |
| EV ratio * Previous feedback * group | 1.31 [0.77, 2.24] | 0.32 |
| EV ratio * Previous feedback (group baseline reversed) | 1.64 [1.21, 2.22] | <0.01 |
| Model 5. *Within the gambling disorder group, do PGSI or GRCS score predict behaviour?* (Table S7b) | | |
| PGSI * EV ratio | 1.11 [1.07, 1.15] | <0.001 |
| GRCS * EV ratio | 1.01 [1.01, 1.02] | <0.001 |

*Note.* Full models reported in supplemental tables. EV = expected value, GRCS = gambling related cognitions scale, PGSI = problem gambling severity index.

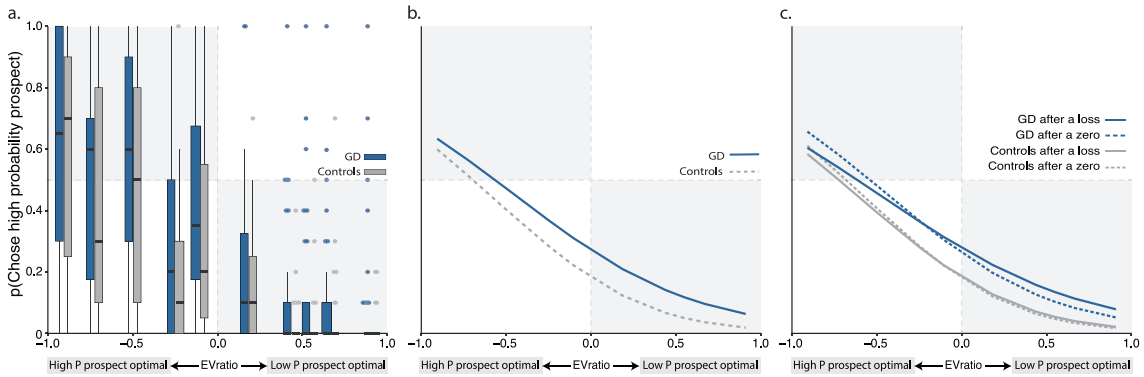


*Fig. 3.* Between group analysis of choice behaviour in the loss version. a) Tukey boxplots of observed behaviour in GD participants and controls. b) Predicted choice behaviour from the logistic regression (Table S2b). Solid line = GD group, dashed line = control group. c) Predicted choice behaviour as a function of previous feedback (Table S5b). Solid lines = choice after a loss outcome, dashed line = choice after a zero outcome. Shaded gray quarters indicate that the high probability prospect is optimal for negative EV ratios, whist the low probability prospect is optimal for positive EV ratios. Blue = GD group, grey = control group. EV, expected value; GD, gambling disorder; P, probability

decision. Our data extend this effect to individuals with gambling disorder, and indicate a likely contributor to the reduced sensitivity to EV information on the current choice.

The group differences in EV sensitivity were observed in both gain and loss-related choices. A group difference in GD on the loss version of the task is contrary to some other findings (Brevers et al., 2012; Ring et al., 2018; van Holst, Veltman, Büchel, Van Den Brink, & Goudriaan, 2012). Notably, in contrast to these previous experiments investigating loss-based decision making and aversive (threat of shock) processing (Brevers et al., 2012; Ring et al., 2018), the present study entailed more complex decisions between two risky lotteries, rather than choices between a certain outcome and a risky lottery. To choose optimally on the VGT, participants are required to estimate both EVs (i.e. integrate probability and magnitude information) and compare those estimates for the two options; these are reasonably demanding decisions. In line with this interpretation, in Brevers et al. (2012) group differences were apparent on decisions when both prospects had similar EVs, rendering the decision reasonably difficult (Brevers et al., 2012; Ring et al., 2018). In our study, the effect of EV ratio

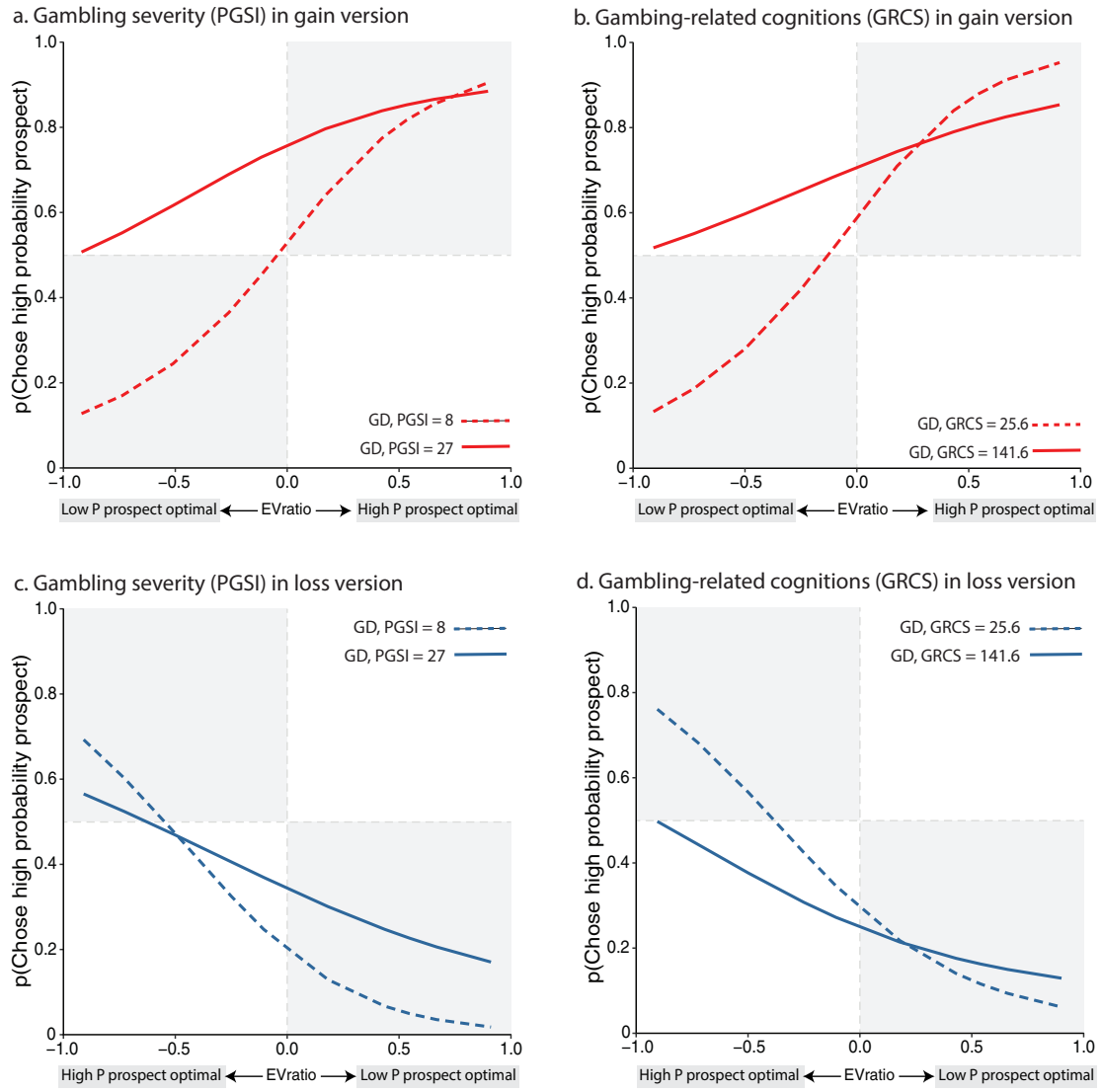


*Fig. 4.* Predicted choice behaviour of GD participants as a function of gambling measures (Table S7). a) Choice behaviour in the gain version as a function of gambling severity with the minimum (dashed line) and maximum (solid line) observed PGSI score. b) Choice behaviour in the gain version as a function of gambling-related cognitions with the minimum (dashed line) and maximum (solid line) observed GRCS score. c) Choice behaviour in the loss version as a function of gambling severity with the minimum (dashed line) and maximum (solid line) observed PGSI score. d) Choice behaviour in the loss version as a function of gambling-related cognitions with the minimum (dashed line) and maximum (solid line) observed GRCS score. Note that the reported odds ratios for GRCS in the text are close to one, as they represent a step change of one unit, but the effect over the possible range of measured scores is a larger effect, as can be seen in these plots. Shaded gray quarters indicate the optimal choice. EV, expected value; GD, gambling disorder; GRCS, gambling related cognitions scale; P, probability; PGSI, problem gambling severity index

was weaker in the loss version across both groups, which could either reflect the increased challenge of calculating EVs in the loss domain, and/or a ceiling effect whereby more participants avoided choices with a high probability of a loss on the negative EV ratio decisions.

Choices in the healthy control group were not driven *purely* by the EV: we saw an evident preference for higher probability gains, and lower probability losses, even when those options are disadvantageous, as indicated by the intercepts (hypothetical EV = 0) in Model 1. These preferences are in line with established biases in healthy decision-making (Kahneman & Tversky, 1979). From visual inspection of the intercepts in Figs. 2 and 3, the gambling disorder group are less susceptible to these two biases, raising a question as to whether they could be 'more rational' than our control group. We disagree with this interpretation, for two reasons. First, the overall percentage of optimal (i.e., EV-consistent) choices did not differ significantly between the groups. Second, the impact of previous feedback information on choice in the gambling disorder group by definition reduces the effect of EV information within a trial, and the random nature of the preceding feedback contributes to the apparent attenuation of the bias observed in controls.

We found no evidence of a group difference in the proportion of advantageous choices. This contrasts with previous research in decision-making under risk (Brand

et al., 2005; Brevers et al., 2012; Lawrence et al., 2009; Wilson & Vassileva, 2018; Zois et al., 2014), in which disadvantageous choice rates were generally increased in gambling disorder. The disparity in the present data could again be due to the relative difficulty of the VGT, requiring the calculation and comparison of the EVs of two gambles, rather than a gamble versus a certain prospect. In addition, the effect of previous feedback on choice in the gambling disorder group reduces the reliance on probability information. As control participants show an overreliance on probability information, which reduces the proportion of rational decisions, the use of preceding information in the gambling disorder group works in the opposite direction to this bias, resulting in no net difference in the overall proportion of rational decisions.

In conclusion, our results support the hypothesis that gambling disorder is associated with a reduction in the use of EV information, and an increase in the use of preceding feedback information, despite the independence of each trial. Calculating EV is essential to minimize risk when gambling, allowing individuals to avoid gambles that might be associated with a high probability of a large loss (e.g. placing a large bet on 00 in roulette, versus a safer smaller bet on red). As a cross sectional design, we are not able to adjudicate whether this reduced sensitivity to EV, and increased influence of the preceding outcome, predates the development of the disorder or arises as a consequence of prolonged gambling (for example leading to increased use of heuristics over EV information). In other recent work, we have investigated biological siblings of people with gambling disorder as a means of separating these influences, where there is evidence for changes in risk-based decision-making associated with gambling disorder vulnerability (Limbrick-Oldfield et al., 2020). Additionally, we cannot say whether individuals with gambling disorder are calculating EV in the same way as control participants, and the group difference is driven by additional interference of preceding outcome information, or whether the way in which EV itself is calculated is different in individuals with gambling disorder.

Our results characterize fundamental alterations in decision processes in gambling disorder, and place these effects in the context of theoretical constructs from behavioural economics. These findings shed light on the psychological mechanisms that may contribute to poor decision-making in gamblers, including the increased sensitivity to prior feedback. These findings could inform the derivation of input variables for risk detection algorithms (e.g. behavioural tracking of online or loyalty card data), and could inform psychological treatments for gambling disorder building on cognitive restructuring and enhancing financial literacy.

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*Authors' contribution:* EHLO, LC, CBG, JJSB and MVC designed the research. DK and CBG collected the data under supervision by LC. EHLO carried out statistical analysis, with input from MVC and DG. EHLO and LC wrote the paper. DG, JJSB, and MVC edited the manuscript.

*Conflict of interest:* EHLO works as a postdoctoral fellow at the Centre for Gambling Research at UBC which is supported by funding from the Province of British Columbia and the British Columbia Lottery Corporation (BCLC), a Canadian Crown Corporation. She has received a speaker honorarium from the Massachusetts Council on Compulsive Gambling (U.S.A.) and accepted travel/accommodation for speaking engagements from the National Council for Responsible Gambling (U.S.A.), the International Multidisciplinary Symposium on Gambling Addiction (Switzerland) and the Responsible Gambling Council (Canada). She has not received any further direct or indirect payments from the gambling industry or groups substantially funded by gambling. LC is the Director of the Centre for Gambling Research at UBC, which is supported by funding from the Province of British Columbia and the British Columbia Lottery Corporation (BCLC), a Canadian Crown Corporation. LC has received a speaker/travel honorarium from the National Association for Gambling Studies (Australia) and the National Center for Responsible Gaming (US), and has receieved fees for academic services from the National Center for Responsible Gaming (US) and Gambling Research Exchange Ontario (Canada). He has not received any further direct or indirect payments from the gambling industry or groups substantially funded by gambling. He has received royalties from Cambridge Cognition Ltd. relating to neurocognitive testing. MVC has received funding from the National Center for Responsible Gaming (US) and a speaker honorarium from the Responsible Gaming Association of New Mexico. JJSB is supported by a Canada Research Chair 950-228984 and the Marianne Koerner Chair in Brain Diseases.The Province of British Columbia government and British Columbia Lottery Corporation had no had no role in the design, analysis, or interpretation of the study, and impose no constraints on publishing.

## SUPPLEMENTARY MATERIAL

Supplementary data to this article can be found online at doi:10.1556/2006.2020.00088

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