"Should've known better": Counterfactual processing in disordered gambling

Yin Wu[1,2], Dawn Kennedy[3], Caylee-Britt Goshko[3], Luke Clark[3]

[1] School of Psychology, Shenzhen University, Shenzhen, China

[2] Shenzhen Key Laboratory of Affective and Social Cognitive Science, Shenzhen University, Shenzhen, China

[3] Centre for Gambling Research at UBC, Department of Psychology and Djavad Mowafaghian Centre for Brain Health, University of British Columbia, Vancouver, British Columbia, Canada

Yin Wu: email yinwu0407@gmail.com

Dawn Kennedy, email: dawnkennedy@psych.ubc.ca

Caylee-Britt Goshko: cgos8950@uni.sydney.edu.au

Luke Clark: email luke.clark@psych.ubc.ca

Address for correspondence to: Dr. Luke Clark, Department of Psychology, University of British Columbia, 2136 West Mall, Vancouver, BC, Canada V6T 1Z4. Contact number: +1 604 827 0618; Email luke.clark@psych.ubc.ca

This is an Author Accepted Manuscript. This paper is not the copy of record and may not exactly replicate the final, authoritative version of the article. Please do not copy or cite without authors' permission. The final article is published as: Wu Y, Kennedy D, Goshko CB, Clark L. "Should've known better": Counterfactual processing in disordered gambling. *Addictive Behaviors*, 2020, 106622.
doi:10.1016/j.addbeh.2020.106622

Funding:

This study was supported by the core funding of the Centre for Gambling Research at UBC. LC holds a Discovery Award from the Natural Sciences and Engineering Research Council of Canada (NSERC; RGPIN-2017-04069). YW is supported by the National Natural Science Foundation of China (31872784, 31600923).

Conflict of interest:

LC is the Director of the Centre for Gambling Research at UBC, which is supported by the Province of British Columbia government and the British Columbia Lottery Corporation (BCLC). The BCLC is a Canadian Crown Corporation. The Province of British Columbia government and BCLC had no involvement in the research design, methodology, conduct, analysis or write-up of the study, and impose no constraints on publishing. LC has received travel/accommodation reimbursements for speaking engagements from the National Center for Responsible Gaming (US) and National Association of Gambling Studies (Australia), and has received honoraria 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. for licensing of a neurocognitive test unrelated to the present study. The other authors declare that they had no conflict of interest with respect to their authorship or the publication of this article.

Abstract

Counterfactual thinking is a component of human decision-making that entails "if only" thinking about unselected choices and outcomes. It is associated with strong emotional responses of regret (when the obtained outcome is inferior to the counterfactual) and relief (vice versa). Counterfactual thinking may play a role in various cognitive phenomena in disordered gambling, such as the effects of near-misses. This study compared individuals with gambling disorder (n = 46) and healthy controls (n = 25) on a behavioural economic choice task that entailed choosing between two gambles, designed to measure counterfactual thinking. Participants provided affect ratings following both the obtained and the non-obtained outcomes. Choices were analyzed using a computational model that derived parameters reflecting sensitivity to expected value, risk variance, and anticipated regret. In the computational choice model, the group with gambling disorder showed increased sensitivity to anticipated regret, reduced sensitivity to expected value, and increased preference for high risk-variance gambles. On the affect ratings, the group with gambling disorder displayed blunted emotional sensitivity to obtained and counterfactual outcomes. Effect sizes of the group differences were modest. Participants with gambling disorder show wide-ranging alterations in decision-making processes and emotional reactivity to choice outcomes. Altered sensitivity to anticipatory regret in gambling disorder may contribute to the development of gambling-related cognitive distortions, and the influences of gambling marketing.

Keywords: Gambling disorder; regret; risk-taking; counterfactual thinking; affective sensitivity

1. Introduction

Gambling disorder (GD) is a behavioural addiction characterized by uncontrolled gambling despite negative consequences (Potenza et al., 2019). Disordered gambling is associated with cognitive distortions that contribute to faulty decision-making during gambling sessions (Clark, 2016; Leonard, Williams, & Vokey, 2015). These distortions centre around the biased processing of random sequences (Oskarsson, Van Boven, McClelland, & Hastie, 2009) and appraisal of skill (Stefan & David, 2013). Gambling-related cognitive distortions are implicated in the aetiology and maintenance of disordered gambling, and are targeted by cognitive therapies for GD (Fortune & Goodie, 2012; Yakovenko et al., 2016). The cognitive architecture and computational mechanisms that underlie these distortions are poorly understood (Ejova & Ohtsuka, 2020).

Emotional factors are also implicated in the development and maintenance of disordered gambling. For example, negative emotional states may motivate gambling as a means of escape (Blaszczynski & Nower, 2002; Devos, Maurage, Clark, & Billieux, 2018), and trait differences in mood-related impulsivity (urgency) and emotion regulation are reliably observed in GD (Billieux et al., 2012; Michalczuk, Bowden-Jones, Verdejo-Garcia, & Clark, 2011). Emotional factors and decision-making coalesce in the phenomenon of regret, and the broader psychological framework of counterfactual thinking (Zeelenberg & Pieters, 2004). Counterfactual thinking refers to the mental processes by which we represent "what might have been": alternative realities to events that occurred (Roese, 1997). Within this framework, regret (and its positive counterpart, relief) is the emotional response that arises when a counterfactual alternative is more (less) favourable that the event that occurred.

In a laboratory choice procedure for eliciting regret (Camille et al., 2004; Mellers, Schwartz, & Ritov, 1999), the participant observes their *obtained outcome* after a choice between two gambles (e.g. lose 70 points), followed by the *non-obtained* *outcome* from the other gamble that was declined (e.g. win 210 points). Although the latter information is effectively irrelevant, emotional ratings and psychophysiological activity are modulated by the counterfactual feedback, in line with the experience of regret and relief (Camille et al., 2004; Wu & Clark, 2015; Wu, van Dijk, Aitken, & Clark, 2016). In addition, the emotional intensity of regret can lead healthy people to make suboptimal choices, in order to minimize their likelihood of experiencing future regret, termed anticipatory regret (Bell, 1982; Loomes & Sugden, 1982; Zeelenberg, Beattie, Van Der Pligt, & De Vries, 1996).

Counterfactual thinking has been implicated in cognitive distortions in gambling. Many lottery players repeatedly choose the same numbers from week to week, because of anticipated regret that they would experience if those numbers won when they had *not* purchased their usual ticket (Wolfson & Briggs, 2002). This effect is often exploited in lottery marketing (Landman & Petty, 2000). It is amplified in the case of 'postcode lotteries', where the counterfactual feedback for non-ticket-holders would be the upsetting sight of their neighbours getting rich (Zeelenberg & Pieters, 2004). Anticipatory regret may play a role in the refusal to sell personally-selected lottery tickets, often regarded as a classic demonstration of illusory control (Bar-Hillel & Neter, 1996; Langer, 1975). Regret is one of several mechanisms invoked to explain the emotional and motivational effects of gambling near-misses (Wu, Dijk, Li, Aitken, & Clark, 2017). For example, near-wins can elicit upward counterfactual thoughts, and continued gambling may serve to alleviate the accompanying state of regret (Loftus & Loftus, 1983).

In this context, it is surprising that regret and counterfactual thinking have received little investigation in GD. Using a behavioural economics approach, two experiments by Tochkov (2009, 2012) inferred an impairment in regret processing in problem gamblers, based on a comparison between choice scenarios designed to elicit differing levels of regret. Along with two self-report studies (Li et al., 2009; Rae & Haw, 2005), this research has been largely predicated on the idea that if a gambler *could* feel and/or anticipate regret, then they would surely avoid persistent gambling. This is supported by neuropsychological data that damage to ventromedial prefrontal cortex -- a brain region implicated in GD -- disrupts regret processing (Camille et al., 2004; Clark, Boileau, & Zack, 2019). However, evidence that counterfactual thinking may contribute to gambling-related cognitive distortions generates the opposing prediction that individuals with GD could be *over*-sensitive to regret and *more* likely to engage in counterfactual thinking. For example, groups with GD may be hyper-sensitive to near-misses (Chase & Clark, 2010; Sescousse et al., 2016). The present study set out to test these competing predictions. Our task (Camille et al., 2004; Mellers et al., 1999) derived affective measures of experienced regret (i.e. the trial-by-trial difference between the obtained and non-obtained outcomes), and we used a computational analysis of gambling choices to parameterize participants' sensitivity to expected value, risk preference, and anticipatory regret, as three latent mechanisms that shape gambling choices on this task (Baskin-Sommers, Stuppy-Sullivan, & Buckholtz, 2016; Gillan et al., 2014; Wu & Clark, 2015). We hypothesized group differences between GD and controls on affective measures of regret sensitivity and the choice parameter reflecting anticipatory regret. Given the competing predictions from the existing literature, we ran two-tailed tests without strong directional predictions. Exploratory analyses within the GD group tested the impact of gambling severity and trait gambling cognitions.

2. Methods

2.1 Participants

Individuals with GD (n = 46; 25 males, 20 females, 1 self-identified as other) were recruited from advertisements on Craigslist.ca (an online message board) and the British Columbia Responsible and Problem Gambling Program. We recruited 26 healthy controls via community advertisements; one control was later excluded for random, unmotivated performance on the task, leaving a control sample of 25 (14 males, 10 females, 1 self-identified as other). The protocol was approved by the Behavioral Research Ethics Board at the University of British Columbia (H15-

00165). Participants provided written informed consent and were reimbursed for their time and travel expenses. GD was confirmed with the SCID-IV structured interview (this was recoded for DSM-5, by removing item 10 and thresholding at 4) and scores ≥ 8 on the Problem Gambling Severity Index (PGSI; Ferris & Wynne, 2001). All participants were aged 19 – 65 years. Exclusion criteria for both groups were: history of neurological illness, previous psychiatric hospitalization, current pharmacotherapy, and significant physical illness.

The healthy controls comprised a mixture of non-gamblers (n = 17) and non-problem gamblers (6 scored 1 on the PGSI, 2 scored 2). GD participants varied in terms of treatment-seeking and stage of treatment: 27 were not treatment-seeking, 15 were currently receiving treatment, and 3 had finished or discontinued treatment, one person did not disclose their treatment status.

Respondents received an initial telephone screen to assess eligibility. Eligible participants attended a 2.5 hour laboratory session, entailing the regret task, an interoception task involving heart beat recording and another decision-making task involving separate blocks of gains-only and losses-only choices. Participants completed the National Adult Reading Test – Revised (Blair & Spreen, 1989) to estimate verbal IQ; the Gambling Related Cognitions Scale (Raylu & Oei, 2004), a 21-item questionnaire that assesses a range of gambling distortions; and the Depression Anxiety and Stress Scale (DASS-21) (Lovibond & Lovibond, 1995) to assess past-week affective symptoms. Other mental health problems were assessed using 8 of the 13 domains in the DSM-5 'Cross Cutting Tool' (American Psychiatric Association, 2013), as the SCID-5 Research Version was not released at the time when we started the study (see Supplementary Materials)

-----------------------insert Table 1 about here-----------------------

2.2 Regret Task (see Figure 1)

Participants performed 80 trials on a 2-choice lottery task modified from Gillan et al. (2014) and programmed in Presentation (Neurobehavioral System Inc.). The first 2 trials were discarded as practice. On each trial, the participant chose between two wheels that displayed different potential gains and losses (see Supplementary Table 4 for trial sequence). Participants were instructed that their total number of points on completion would be honored as a cash bonus loaded on a gift card, to a maximum of CAD$10. Following the obtained outcome (2 s duration; termed ‘partial feedback’), participants rated “How pleased were you with the outcome?” (1 = *extremely unpleasant* and 9 = *extremely pleasant*). The non-obtained outcome (on the non-selected wheel) was then revealed for 2 s, alongside the obtained outcome. At this complete feedback stage, participants provided a second affect rating. The inter-trial interval was 2 s. No time constraints were imposed on wheel selection or affect ratings. Outcomes were pre-specified to be in line with the displayed probabilities, ensuring that the task was fair.

-----------------------insert Figure 1 about here-----------------------

2.3 Statistical analysis

2.3.1 Affect ratings. We used R and *lme4* (Bates, Maechler, & Bolker, 2012) to perform linear mixed effects analyses on the affect ratings, with Group as a fixed effect and participant number as a random effect. We conducted separate analyses on the first rating (following partial feedback) and the second rating (following complete feedback). The partial feedback models tested the influence of i) the obtained outcome, and ii) the difference between the obtained outcome and the non-obtained outcome *on the chosen wheel* (the ‘chance counterfactual’, following Gillan et al. 2014). For the second rating, the complete feedback models tested the influence of i) the obtained outcome, ii) the difference between the obtained outcome and the non-obtained outcome *on the other wheel* (termed the ‘agent counterfactual’ after Gillan et al. 2014). These outcome expressions were entered as continuous fixed-effect predictors. The healthy control group were the reference category for the Group factor, hence the terms for the outcome predictors refers to the influence of those predictors within the healthy group. To test the analogous effects in the GD group, a subset model was run restricted to that group.

2.3.2 Choice Model. A computational model was applied to the trial-by-trial choice behavior, based on Gillan et al. (2014), to predict participants' wheel selections. The model considered the influence of three parameters: expected value (*e*), risk variance (*v*) and anticipated regret (*r*). For wheel 1 (W_1): x_1 and y_1 refer to the two possible outcomes, where $x_1 > y_1$; p and 1-p are their respective probabilities. For wheel 2 (W_2), the outcomes are x_2 and y_2 ($x_2 > y_2$) and their respective probabilities q and 1-q. Using this notation, the expected value (EV) of W_1 is calculated using: $\mathrm{EV} = \mathrm{px}_1 + (1 - \mathrm{p})\mathrm{y}_1$. The *e* parameter is then calculated by subtracting the EV of W_2 from the EV of W_1: $e = \mathrm{EV}_{\mathrm{W1}} - \mathrm{EV}_{\mathrm{W2}} = [\mathrm{px}_1 + (1 - \mathrm{p})\mathrm{y}_1] - [\mathrm{qx}_2 + (1 - \mathrm{q})\mathrm{y}_2]$
If *e* is positive, then a participant who is sensitive to (higher) EV should choose W_1.

The risk variance parameter, *v*, is the comparison of the two mathematical variance terms for the wheels, based on the probability density function. The risk variance for W_1 is calculated using: $\mathrm{var} = \mathrm{p}(\mathrm{x}_1 - \mathrm{EV}_{\mathrm{W1}})^2 + (1 - \mathrm{p})(\mathrm{y}_1 - \mathrm{EV}_{\mathrm{W1}})^2$
Thus the comparison across the two wheels is calculated as:

$$v = v_{\mathrm{W2}} - v_{\mathrm{W1}}$$
$$= [\mathrm{q}(\mathrm{x}_2 - \mathrm{EV}_{\mathrm{W2}})^2 + (1 - \mathrm{q})(\mathrm{y}_2 - \mathrm{EV}_{\mathrm{W2}})^2] - [\mathrm{p}(\mathrm{x}_1 - \mathrm{EV}_{\mathrm{W1}})^2 + (1 - \mathrm{p})(\mathrm{y}_1 - \mathrm{EV}_{\mathrm{W1}})^2]$$

If *v* is positive, then W_1 is associated with lower risk variance and a risk averse participant should select that wheel.

The anticipated regret calculation considers the difference between the worst outcome on a wheel and best outcome on the other wheel: for W_1, $(\mathrm{y}_1 - \mathrm{x}_2)$. To a regret avoidant participant, a large difference is unattractive. The *r* parameter is calculated by subtracting the regret term on W_2 from W_1:

$$r = (\mathrm{y}_1 - \mathrm{x}_2) - (\mathrm{y}_2 - \mathrm{x}_1)$$

A participant who anticipates (and avoids) regret should select W_1 if *r* is positive and select W_2 if r is negative.

Using these three parameters, the probability of choosing wheel 1 (Pw_{it}), where t denotes trial (or time) and i denotes individual, is calculated using:

$$P(W_{1it}) = 1 - P(W_{2it}) = F(e_{it}, v_{it}, r_{it})$$

F is the inverse logit function, $F(\theta) = e^{\theta}(1 + e^{\theta})$ and θ is the logit predicted by the individual values of *e*, *v*, and *r* in the logistic regression. To account for differences in scaling and to aid interpretation, the three parameters were standardized for entry in the model. Within-subjects logistic regression analysis was performed using the lme4::lmer function, with the model Choice ~ *e* + *v* + *r* + Group:*e* + Group:*v* + Group:*r* + (1|subject). Choice is a binary variable, coded 1 for wheel_1 and 0 for wheel_2; group is a fixed-effect factor; subject is a random-effect factor; *e*, *v*, and *r* are continuous fixed-effect predictors. Logit and inverse logit functions are defined as $\text{logit}(\theta) = \ln[\theta/(1-\theta)]$ and $\text{invlogit}(\theta) = e^{\theta}(1 + e^{\theta})$, such that $\text{invlogit}[\text{logit}(\theta)] = \theta$. For the ratings and choice models, the effect size for the group interaction terms were calculated with Cohen's f^2 (small 0.02, medium 0.15, large 0.35), based on the difference in R^2 for models with and without the interaction term included $f^2 = \Delta R^2 / (1 - R^2)$ (Selya, Rose, Dierker, Hedeker, & Mermelstein, 2012). Data analysis code in R is available at https://github.com/CGR-UBC/Regret_GD_2020.

3. Results

3.1 Demographic and Clinical Characteristics of the Groups

Group characteristics are reported in Table 1. The groups were comparable in terms of gender. The GD group were 6.4 years older on average (95% CI: -12.9, 0.04, $p = .051$); age is explored in the analyses of individual differences (see Supplemental Material) as a variable that has been previously related to regret-based choice. In GD, the preferred form of gambling was land-based slot machine gambling (46%), following by online gambling (15%) and sports betting (10%). The GD group scored significantly higher on the gambling-related cognitions (GRCS) and affective symptoms (DASS).

3.2 Regret task

In terms of overall points earned on the task, the GD group (*M* = 993.70, *SD* = 687.38) did not differ from the control group (*M* = 834.40, *SD* = 663.13), $t(69) = 0.944$, 95% CI: -495.6, 177.3, $p = .348$. There were no group differences in decision latencies (see Supplemental Table 2).

3.2.1 Affect ratings to partial feedback

The first ratings were regressed on obtained outcome and group. There was an effect of the obtained outcome, $b = 0.0135$, $SE = 0.000218$, 95% CI: 0.0130, 0.0139, $t = 61.6$, $p < .001$: in the healthy controls (the reference category), a 100 point increase in the obtained outcome predicted an affect change of 1.3 units on the 1-9 scale. A significant interaction term for obtained outcome x group, $b = -0.000708$, $SE = 0.000271$, 95% CI: -0.0012, -0.0002, $t = -2.61$, $p = .009$, $f^2 = 0.0011$, indicated that this relationship was reduced in GD (see Figure 2A). Nevertheless, the effect of obtained outcome remained significant in GD in the subset model, $b = 0.0128$, $SE = 0.000165$, 95% CI: 0.0124, 0.0131, $t = 77.2$, $p < .001$.

------------------------insert Figure 2 about here------------------------

The effect of the chance counterfactual was significant, $b = 0.00694$, $SE = 0.000135$, 95% CI: 0.00667, 0.00720, $t = 51.4$, $p < .001$: in controls, a 100 point increase in the difference between the obtained outcome and the non-obtained on the chosen wheel, predicted an affect change of 0.7 units on the 1-9 point scale. The chance counterfactual x group interaction term was significant, showing that this relationship was attenuated in the GD group, $b = -0.000345$, $SE = 0.000167$, % CI: -0.000672, -0.000018, $t = -2.07$, $p = 0.039$, $f^2 = .0007$. In the subset model, the chance counterfactual term remained significant in the GD group, b = 0.00660, SE = 0.0000994, 95% CI: 0.00640, 0.00679, t = 66.4, p < .001.

3.2.2 Affect ratings to complete feedback.

On the second rating, the significant effect of the obtained outcome was corroborated, b = 0.0103, SE = 0.000299, 95% CI: 0.00973, 0.0109, t = 34.5, p < .001, as well as the obtained outcome x group interaction term, b = -0.00105, SE = 0.000370, 95% CI: -0.00177, -0.00032, t = -2.83, p = 0.005, f^2 = 0.0014, due to a weaker relationship in the GD group.

The effect of the agent counterfactual term was significant, b = 0.0106, SE = 0.000219, 95% CI: 0.0102, 0.0110, t = 48.5, p < .001: in controls, a 100 point increase in the difference between the obtained outcome and non-obtained outcome on the unchosen wheel, predicted an affect change on 1.1 units on the 1-9 scale. The agent counterfactual x group interaction term was also significant, b = -0.000608, SE = 0.000273, 95% CI: -0.00114, 0.00007, t = -2.23, p = .026, f^2 = 0.0008, such that the effect of the counterfactual feedback was attenuated in GD (see Figure 2D). The GD group were sensitive to this predictor in the subset model, b = 0.0100, SE = 0.000167, 95% CI: 0.00968, 0.0103, t = 59.8, p < .001.

3.2.3 Choice Model

The choice parameters e and r exerted significant effects (see Table 2) (odds ratios e = 3.36, v = 0.91, r = 1.53). Thus, in the healthy controls, the likelihood of choosing a gamble increased with expected value (odds ratio = 3.3) and with the regret parameter (odds ratio = 1.5) (i.e. participants minimized anticipatory regret).

------------------------insert Table 2 and Figure 3 about here------------------------

The group interaction terms revealed significant differences in the GD group on each of the three parameters: reduced sensitivity to expected value (e), increased choice of high risk variance gambles (*v*), and higher regret anticipation (*r*) (see Table 2 and Figure 3), albeit with modest effect sizes (f^2 = 0.0015 to 0.0047). In the GD subset model, each of the three choice parameters exerted a significant effect (odds ratios *e* = 2.57, *v* = 0.72, *r* = 1.76).

3.2.4 Sensitivity Analyses

Sensitivity analyses tested associations in the GD group between the regret task measures and four covariates: GRCS score, gambling severity, age, and smoking. Significant correlations were observed between some task measures, but the task measures were not significantly associated with the four covariates (see Supplementary Table 3).

4. Discussion

The present study examined counterfactual thinking in GD using a choice task that recorded emotional ratings to gamble outcomes as well as computational modeling of the choices themselves. We tested the hypotheses that GD would have altered regret sensitivity on affect ratings, and altered tendency to use anticipated regret in guiding their choices. On the affect ratings, we found evidence for blunted emotional responses to objective and counterfactual outcomes in GD, although confidence intervals for the subset models indicated that the GD group still robustly used these sources of information. This effect was seen to both levels of counterfactual information, as well as to the obtained feedback, pointing to a generalized reduction in emotional reactivity rather than a specific effect on regret processing. In the choice model, we found evidence for a greater sensitivity to anticipatory regret in the GD group, as well as reduced sensitivity to expected value and increased risk preference. There were no evidence of alterations in choice latencies or overall earnings on the task.

In line with our affect ratings, functional imaging data in GD also indicate decreased neural activity to financial gains and losses (Balodis et al., 2012; Reuter et al., 2005), albeit with some inconsistency (Clark et al., 2019). The increased risk attitude (v) parameter observed here in GD is also consistent with prior neurocognitive studies showing elevated risk-taking (Brand et al., 2005; Brevers et al., 2012; Lawrence, Luty, Bogdan, Sahakian, & Clark, 2009; Ligneul, Sescousse, Barbalat, Domenech, & Dreher, 2013). Some studies have indicated reduced sensitivity to mathematical expectancies in GD, e.g. displayed probabilities on the Cambridge Gamble Task (Lawrence et al., 2009; Limbrick-Oldfield et al., 2020; Ring et al., 2018). However, the evidence here that regret anticipation is increased in GD contrasts with prior research by Tochkov (2009, 2012), which used indirect comparisons (e.g. between hypothetical and actual gambles) to infer impaired regret processing in problem gamblers (SOGS 3+). Tochkov also used 'at-risk' gamblers as a comparison group, and her findings could therefore indicate quantitative rather than qualitative differences within the gambling risk spectrum.

The differences in regret processing in GD contrasts with some prior neuropsychological research in other populations. In cases with orbitofrontal cortex lesions, emotional ratings to regret and regret choice sensitivity were both reduced (Camille et al., 2004). Thus, our results do not support a simple account of orbitofrontal pathophysiology in GD. Our data also mirror a pattern reported in obsessive compulsive disorder, in which emotional ratings to regret and relief were enhanced, and the regret choice parameter was reduced (Gillan et al., 2014). There is longstanding interest in the aetiological relationship between GD and OCD (Potenza, 2006), and these findings may be reconciled by a compulsivity spectrum cutting across multiple disorders (Gillan, Kosinski, Whelan, Phelps, & Daw, 2016; Tavares & Gentil, 2007). Future work may usefully employ direct measures of compulsivity alongside regret.

The evidence for increased engagement with counterfactual processing in GD could fuel the development of gambling-related cognitive distortions including the effects of near-misses (Wu et al., 2017), over-confidence (Petrocelli & Crysel, 2009) and preferences for illusory control. These distortions – at a broad level - are elevated in GD (Goodie, 2005; Orgaz, Estevez, & Matute, 2013; Sescousse et al., 2016). However, this interpretation would predict significant correlations between the regret measures and the GRCS, for which we did not find support (the r^2 indicates only 3% shared variance). Indeed, we did not find evidence relating regret processing to any of the tested sources of individual differences, including symptom severity. For the GRCS, we note that this scale does not emphasize some of the specific distortions that are linked to counterfactual thinking (e.g. no items pertain to near-misses). The correlational analyses by GRCS and PGSI could also have been compromised by heterogeneity in our GD group in terms of treatment stage (Breen, Kruedelbach, & Walker, 2001).

Some further limitations should be noted. First, our hypotheses were not pre-registered and must be treated as exploratory. In interpreting our beta coefficients, the task predictors (e.g. the counterfactual outcome terms) exerted substantial changes on the affect ratings. However, our group interaction terms, while statistically significant, had effect sizes below the threshold for a small effect. These modest effect sizes may reflect the group differences being predominantly expressed on a subset of trials; for example, the group difference in regret is likely driven by a subset of trials on which the potential for regret is high. Second, our GD group differed somewhat from our control group in terms of age and also smoking. We did not find evidence relating these variables with regret within the GD group (Supplemental Table 3) but they could still contribute to group differences, plus it is possible that other demographic variables that were similar across the groups could nevertheless moderate regret-related processing. Third, our decision-making task operationalizes regret based on the emotional impact of non-obtained (i.e. rejected) outcomes, and although this task is well-validated, there are other facets of counterfactual thinking that could be relevant to gambling. The consequences of inaction (termed omission bias) or changing one's mind could be relevant to gamblers switching between games, such as individual slot machines (Paliwal, Petzschner, Schmitz, Tittgemeyer, & Stephan, 2014).

Our findings indicate that regret and counterfactual thinking may be neglected psychological constructs with relevance to disordered gambling, lying at the intersection of emotion and decision-making. A strength of our study is that it leverages a task that is well characterized at both computational and behavioural neuroscience levels (Kishida et al., 2015; Steiner & Redish, 2014). In term of application, we note that the emotional power of regret is not exclusively detrimental to decision-making: because the over-riding strategy is regret minimization (Zeelenberg et al., 1996), the anticipation of regret can bias individuals either towards or away from risky options. If regret is amplified in disordered gamblers, this carries implications for gambling advertising that might harness regret (Landman & Petty, 2000; Zeelenberg & Pieters, 2004). At the same time, these cognitive differences highlight the possible use of gambling-related regret in public messaging and prevention programs to reduce gambling harms.

References

American Psychiatric Association. (2013). Online Assessment Tools. Retrieved from https://www.psychiatry.org/psychiatrists/practice/dsm/educational-resources/assessment-measures

Balodis, I. M., Kober, H., Worhunsky, P. D., Stevens, M. C., Pearlson, G. D., & Potenza, M. N. (2012). Diminished frontostriatal activity during processing of monetary rewards and losses in pathological gambling. *Biological Psychiatry*, *71*, 749–757. https://doi.org/10.1016/j.biopsych.2012.01.006

Bar-Hillel, M., & Neter, E. (1996). Why are people reluctant to exchange lottery tickets? *Journal of Personality and Social Psychology*, *70*(1), 17–27. https://doi.org/10.1037/0022-3514.70.1.17

Baskin-Sommers, A., Stuppy-Sullivan, A. M., & Buckholtz, J. W. (2016). Psychopathic individuals exhibit but do not avoid regret during counterfactual decision making.

Proceedings of the National Academy of Sciences, *113*(50), 14438–14443. https://doi.org/10.1073/pnas.1609985113

Bates, D., Maechler, M., & Bolker, B. (2012). lme4: Linear mixed-effects models using S4 classes.

Bell, D. E. (1982). Regret in decision-making under uncertainty. *Operations Research*, *30*, 961–981. Retrieved from https://doi.org/10.1287/opre.30.5.961

Billieux, J., Lagrange, G., Van der Linden, M., Lançon, C., Adida, M., & Jeanningros, R. (2012). Investigation of impulsivity in a sample of treatment-seeking pathological gamblers: A multidimensional perspective. *Psychiatry Research*, *198*, 291–296. https://doi.org/10.1016/j.psychres.2012.01.001

Blair, J. R., & Spreen, O. (1989). Predicting premorbid IQ: a revision of the national adult reading test. *Clinical Neuropsychology*, *3*, 129–136. Retrieved from https://doi.org/10.1080/13854048908403285

Blaszczynski, A., & Nower, L. (2002). A pathways model of problem and pathological gambling. *Addiction*, *97*, 487–499.

Brand, M., Kalbe, E., Labudda, K., Fujiwara, E., Kessler, J., & Markowitsch, H. J. (2005). Decision-making impairments in patients with pathological gambling. *Psychiatry Research*, *133*(1), 91–99. Retrieved from https://doi.org/10.1016/j.psychres.2004.10.003

Breen, R. B., Kruedelbach, N. G., & Walker, H. I. (2001). Cognitive changes in pathological gamblers following a 28-day inpatient program. *Psychology of Addictive Behaviors*, *15*(3), 246–248. Retrieved from https://doi.org/10.1037/0893-164X.15.3.246

Brevers, D., Cleeremans, A., Goudriaan, A. E., Bechara, A., Kornreich, C., Verbanck, P., & Noel, X. (2012). Decision making under ambiguity but not under risk is related to problem gambling severity. *Psychiatry Research*, *200*(2–3), 568–574. https://doi.org/10.1016/j.psychres.2012.03.053

Camille, N., Coricelli, G., Sallet, J., Pradat-Diehl, P., Duhamel, J. R., & Sirigu, A. (2004). The involvement of the orbitofrontal cortex in the experience of regret. *Science*, *304*, 1167–1170. https://doi.org/10.1126/science.1094550

Chase, H. W., & Clark, L. (2010). Gambling severity predicts midbrain response to near-miss outcomes. *Journal of Neuroscience*, *30*, 6180–6187. https://doi.org/10.1523/JNEUROSCI.5758-09.2010

Clark, L. (2016). Decision-making in Gambling Disorder: understanding behavioural addictions. In J.-C. Dreher & L. K. Tremblay (Eds.), *Decision Neuroscience*. Elsevier. https://doi.org/10.1017/CBO9781107415324.004

Clark, L., Boileau, I., & Zack, M. (2019). Neuroimaging of reward mechanisms in Gambling disorder: an integrative review. *Molecular Psychiatry*, *24*, 674–693. https://doi.org/10.1038/s41380-018-0230-2

Devos, G., Maurage, P., Clark, L., & Billieux, J. (2018). Induced sadness increases persistence in a simulated slot machine task among recreational gamblers. *Psychology of Addictive Behaviors*, *32*, 383–388. https://doi.org/10.1037/adb0000364

Ejova, A., & Ohtsuka, K. (2020). Erroneous gambling-related beliefs emerge from broader beliefs during problem-solving: a critical review and classification scheme. *Thinking & Reasoning*, *26*, 159–187. https://doi.org/10.1080/13546783.2019.1590233

Ferris, J., & Wynne, H. (2001). The Canadian problem gambling index. *Ottawa, ON: Canadian Centre on Substance Abuse*.

Fortune, E. E., & Goodie, A. S. (2012). Cognitive distortions as a component and treatment focus of pathological gambling: A review. *Psychology of Addictive Behaviors*, *26*, 298–310. https://doi.org/10.1037/a0026422

Gillan, C. M., Kosinski, M., Whelan, R., Phelps, E. A., & Daw, N. D. (2016). Characterizing a psychiatric symptom dimension related to deficits in goaldirected control. *ELife*, *5*, e11305. https://doi.org/10.7554/eLife.11305

Gillan, C. M., Morein-Zamir, S., Kaser, M., Fineberg, N. a., Sule, A., Sahakian, B. J., … Robbins, T. W. (2014). Counterfactual processing of economic action-outcome alternatives in obsessive-compulsive disorder: Further evidence of impaired goal-directed behavior. *Biological Psychiatry*, *75*(8), 639–646. https://doi.org/10.1016/j.biopsych.2013.01.018

Goodie, A. S. (2005). The role of perceived control and overconfidence in pathological gambling. *Journal of Gambling Studies*, *21*(4), 481–502. https://doi.org/10.1007/s10899-005-5559-1

Kishida, K. T., Saez, I., Lohrenz, T., Witcher, M. R., Laxton, A. W., Tatter, S. B., … Montague, P. R. (2015). Subsecond dopamine fluctuations in human striatum encode superposed error signals about actual and counterfactual reward. *Proceedings of the National Academy of Sciences*, 201513619. https://doi.org/10.1073/pnas.1513619112

Landman, J., & Petty, R. (2000). "It could have been you": how states exploit counterfactual thought to market lotteries. *Psychology and Marketing*, *17*(4), 299–321. https://doi.org/10.1002/(SICI)1520-6793(200004)17:4<299::AID-MAR3>3.0.CO;2-E

Langer, E. J. (1975). The illusion of control. *Journal of Personality and Social Psychology*, *32*, 311–328. https://doi.org/10.1037/0022-3514.32.2.311

Lawrence, A. J., Luty, J., Bogdan, N. A., Sahakian, B. J., & Clark, L. (2009). Problem gamblers share deficits in impulsive decision-making with alcohol-dependent individuals. *Addiction*, *104*(6), 1006–1015. https://doi.org/10.1111/j.1360-0443.2009.02533.x

Leonard, C. A., Williams, R. J., & Vokey, J. (2015). Gambling fallacies: what are they and how are they best measured? *Addiction Research & Therapy*, *6*(4), 1–9. https://doi.org/10.4172/2155-6105.1000256

Li, S., Zhou, K., Sun, Y., Rao, L.-L., Zheng, R., & Liang, Z.-Y. (2009). Anticipated regret, risk perception, or both: which is most likely responsible for our intention to gamble? *Journal of Gambling Studies*, *26*(1), 105–116. https://doi.org/10.1007/s10899-009-9149-5

Ligneul, R., Sescousse, G., Barbalat, G., Domenech, P., & Dreher, J.-C. (2013). Shifted risk preferences in pathological gambling. *Psychological Medicine*, *43*(5), 1059–1068. https://doi.org/10.1017/S0033291712001900

Limbrick-Oldfield, E. H., Mick, I., Cocks, R. E., Flechais, R. S. A., Turton, S., Lingford-Hughes, A., … Clark, L. (2020). Neural and neurocognitive markers of vulnerability to gambling disorder: a study of unaffected siblings. *Neuropsychopharmacology*, *45*(2), 292–300. https://doi.org/10.1038/s41386-019-0534-1

Loftus, G. R., & Loftus, E. F. (1983). *Mind at Play: the Psychology of Video Games*. New York: Basic Books.

Loomes, G., & Sugden, R. (1982). Regret Theory: an alternative theory of rational choice under uncertainty. *Economic Journal*, *92*(368), 805–824. Retrieved from https://www.jstor.org/stable/2232669

Lovibond, P. F., & Lovibond, S. H. (1995). *Manual for the Depression Anxiety Stress Scales (2nd ed.)*. Sydney, N.S.W: Psychology Foundation of Australia.

Mellers, B. A., Schwartz, A., & Ritov, I. (1999). Emotion-based choice. *Journal of Experimental Psychology: General*, *128*, 332–345. Retrieved from https://doi.org/10.1037/0096-3445.128.3.332

Michalczuk, R., Bowden-Jones, H., Verdejo-Garcia, A., & Clark, L. (2011). Impulsivity and cognitive distortions in pathological gamblers attending the UK National Problem Gambling Clinic: a preliminary report. *Psychological Medicine*, *41*, 2625–2635. https://doi.org/10.1017/S003329171100095X

Orgaz, C., Estevez, A., & Matute, H. (2013). Pathological gamblers are more vulnerable to the illusion of control in a standard associative learning task. *Frontiers in Psychology*, *4*, 306. https://doi.org/10.3389/fpsyg.2013.00306

Oskarsson, A. T., Van Boven, L., McClelland, G. H., & Hastie, R. (2009). What's next? Judging sequences of binary events. *Psychological Bulletin*, *135*(2), 262–285. https://doi.org/10.1037/a0014821

Paliwal, S., Petzschner, F. H., Schmitz, A. K., Tittgemeyer, M., & Stephan, K. E. (2014). A model-based analysis of impulsivity using a slot-machine gambling paradigm. *Frontiers in Human Neuroscience*, *8*, 1–17. https://doi.org/10.3389/fnhum.2014.00428

Petrocelli, J. V., & Crysel, L. C. (2009). Counterfactual thinking and confidence in blackjack: A test of the counterfactual inflation hypothesis. *Journal of Experimental Social Psychology*, *45*(6), 1312–1315.

https://doi.org/10.1016/j.jesp.2009.08.004

Potenza, M. N. (2006). Should addictive disorders include non-substance-related conditions? *Addiction*, *101 Suppl*, 142–151. https://doi.org/ADD1591 [pii]10.1111/j.1360-0443.2006.01591.x

Potenza, M. N., Balodis, I. M., Derevensky, J., Grant, J. E., Petry, N. M., Verdejo-garcia, A., & Yip, S. W. (2019). Gambling Disorder. *Nature Reviews Disease Primers*, *5*, 51. https://doi.org/10.1038/s41572-019-0099-7

Rae, D., & Haw, J. (2005). The effect of depression and perceived skill on anticipated emotions and persistence in off-course betting. *International Gambling Studies*, *5*(2), 199–208. https://doi.org/10.1080/14459790500303386

Raylu, N., & Oei, T. P. S. (2004). The Gambling Related Cognitions Scale (GRCS): development, confirmatory factor validation and psychometric properties. *Addiction*, *99*(6), 757–769. https://doi.org/10.1111/j.1360-0443.2004.00753.x

Reuter, J., Raedler, T., Rose, M., Hand, I., Glascher, J., & Buchel, C. (2005). Pathological gambling is linked to reduced activation of the mesolimbic reward system. *Nature Neuroscience*, *8*, 147–148. Retrieved from https://doi.org/10.1038/nn1378

Ring, P., Probst, C. C., Neyse, L., Wolff, S., Kaernbach, C., van Eimeren, T., … Schmidt, U. (2018). It's all about gains: risk preferences in problem gambling. *Journal of Experimental Psychology: General*, *147*(8), 1241–1255. https://doi.org/10.1037/xge0000418

Roese, N. J. (1997). Counterfactual thinking. *Psychological Bulletin*, *121*(1), 133–148. https://doi.org/10.1037/0033-2909.121.1.133

Selya, A. S., Rose, J. S., Dierker, L. C., Hedeker, D., & Mermelstein, R. J. (2012). A practical guide to calculating Cohen's f2, a measure of local effect size, from PROC MIXED. *Frontiers in Psychology*, *3*, 111. https://doi.org/10.3389/fpsyg.2012.00111

Sescousse, G., Janssen, L. K., Hashemi, M. M., Timmer, M. H., Geurts, D. E., Ter Huurne, N. P., … Cools, R. (2016). Amplified striatal responses to near-miss outcomes in pathological gamblers. *Neuropsychopharmacology*, *41*, 2614–2623.

https://doi.org/10.1038/npp.2016.43

Stefan, S., & David, D. (2013). Recent developments in the experimental investigation of the illusion of control. A meta-analytic review. *Journal of Applied Social Psychology*, *43*, 377–386. Retrieved from https://doi.org/10.1111/j.1559-1816.2013.01007.x

Steiner, A. P., & Redish, A. D. (2014). Behavioral and neurophysiological correlates of regret in rat decision-making on a neuroeconomic task. *Nature Neuroscience*, *17*, 995–1002. https://doi.org/10.1038/nn.3740

Tavares, H., & Gentil, V. (2007). Pathological gambling and obsessive-compulsive disorder: Towards a spectrum of disorders of volition. *Revista Brasileira de Psiquiatria*, *29*(2), 107–117. Retrieved from http://dx.doi.org/10.1590/S1516-44462007000200005

Tochkov, K. (2009). The effects of anticipated regret on risk preferences of social and problem gamblers. *Judgment and Decision Making*, *4*(3), 227–234. Retrieved from http://gateway.nvdpl.ca:2048/docview/1011226077?accountid=46601

Tochkov, K. (2012). No regrets? Mood and the anticipation of emotions in problem gambling. *International Gambling Studies*, *12*(1), 39–53. https://doi.org/10.1080/14459795.2011.611525

Wolfson, S., & Briggs, P. (2002). Locked into gambling: anticipatory regret as a motivator for playing the National Lottery. *Journal of Gambling Studies*, *18*(1), 1–17. Retrieved from https://doi.org/10.1023/A:1014548111740

Wu, Y., & Clark, L. (2015). Disappointment and regret enhance corrugator reactivity in a gambling task. *Psychophysiology*, *52*(4), 518–523. https://doi.org/10.1111/psyp.12371

Wu, Y., Dijk, van E., Li, H., Aitken, M., & Clark, L. (2017). On the counterfactual nature of gambling near-misses: an experimental study. *Journal of Behavioral Decision Making*, *30*(4), 855–868. https://doi.org/10.1002/bdm.2010

Wu, Y., van Dijk, E., Aitken, M. R. F., & Clark, L. (2016). Missed losses loom larger than missed gains: Electrodermal reactivity to decision choices and outcomes in a gambling task. *Cognitive, Affective and Behavioral Neuroscience*, *16*, 353–361.

Retrieved from https://doi.org/10.3758/s13415-015-0395-y

Yakovenko, I., Hodgins, D. C., El-Guebaly, N., Casey, D. M., Currie, S. R., Smith, G. J., … Schopflocher, D. P. (2016). Cognitive distortions predict future gambling involvement. *International Gambling Studies*, *16*, 175–192. https://doi.org/10.1080/14459795.2016.1147592

Zeelenberg, M., Beattie, J., Van Der Pligt, J., & De Vries, N. K. (1996). Consequences of regret aversion: Effects of expected feedback on risky decision making. *Organizational Behavior and Human Decision Processes*, *65*(2), 148–158. https://doi.org/10.1006/obhd.1996.0013

Zeelenberg, M., & Pieters, R. (2004). Consequences of regret aversion in real life: the case of the Dutch postcode lottery. *Organizational Behavior and Human Decision Processes*, *93*(2), 155–168. https://doi.org/10.1016/j.obhdp.2003.10.001

Table 1. Group characteristics

	Gambling Disorder	Controls	
Age (years)	42.65 (12.74)	36.2 (13.7)	t(69) = 1.983, p = .051
Gender	F = 20 M = 25	F = 10 M = 14	χ^2 = 0.246, p = .884
NART	93.76 (8.32)	91.65 (8.97)	t(69) = -.994, p = .323
PGSI	17.02 (4.87)	0.40 (0.65)	N/A
GRCS	84.40 (23.77)	34.08 (10.66)	t(69) = 12.3, p < .001
DASS	22.46 (12.08)	10.20 (6.31)	t(69) = 5.61, p < .001
Smoking	23 smokers	2 smokers	χ^2 = 12.5, p < 0.001
FTND (in smokers)	3.83 (2.50)	2.50 (3.54)	t(23) = 0.71, p = .488

NART = National Adult Reading Test (Revised) verbal subscale; PGSI = Problem Gambling Severity Index (note we do not report the inferential test on PGSI as this variable was inclusionary); GRCS = Gambling Related Cognitions Scale; DASS = Depression Anxiety and Stress Scale; FTND = Fagerstrom Test of Nicotine Dependence.

Table 2. Model of Choice Behavior

Parameter	beta	SE	95% CI	OR	z	*p*
(A) Choice model with all subjects						
Intercept	0.120	0.043	0.033, 0.208	1.13	2.74	.006
e	1.210	0.096	1.029, 1.404	3.36	12.64	< .001
v	-0.099	0.055	-0.208, 0.009	0.91	-1.78	.075
r	0.425	0.054	0.319, 0.533	1.53	7.81	< .001
e*group	-0.257	0.114	-0.485, -0.036	0.77	-2.25	.024
v*group	-0.235	0.069	-0.371, -0.099	0.79	-3.39	<.001
r*group	0.140	0.068	0.007, 0.274	1.15	2.06	.039
71 subjects, 5460 observations. Log Likelihood: -3135.1						
(B) Choice model in the GD group						
intercept	0.0778	0.048	-0.018, 0.174	1.08	1.618	.106
e	0.944	0.063	0.823, 1.071	2.57	14.96	< .001
v	-0.331	0.042	-0.413, -0.250	0.72	-7.96	< .001
r	0.563	0.041	0.483, 0.644	1.76	13.73	< .001
46 subjects, 3521 observations. Log Likelihood: -2031.5						

e = expected value, v = risk variance, r = anticipated regret. The three choice parameters were z transformed for entry, different their different ranges. OR = odds ratio for the beta coefficient

Figure 1. Sequence of events comprising a single trial of the regret task. All outcome probabilities were 0.25, 0.5, or 0.75, as indicated by the size of the segment, and all magnitudes were drawn from +70, +210, -70, -210. In this trial, the obtained outcome (-210 points, a loss) is worse than the non-obtained outcome (+70 points, a gain) and thus presentation of the non-obtained feedback should elicit regret, expressed as lower affect on rating 2 compared to rating 1.

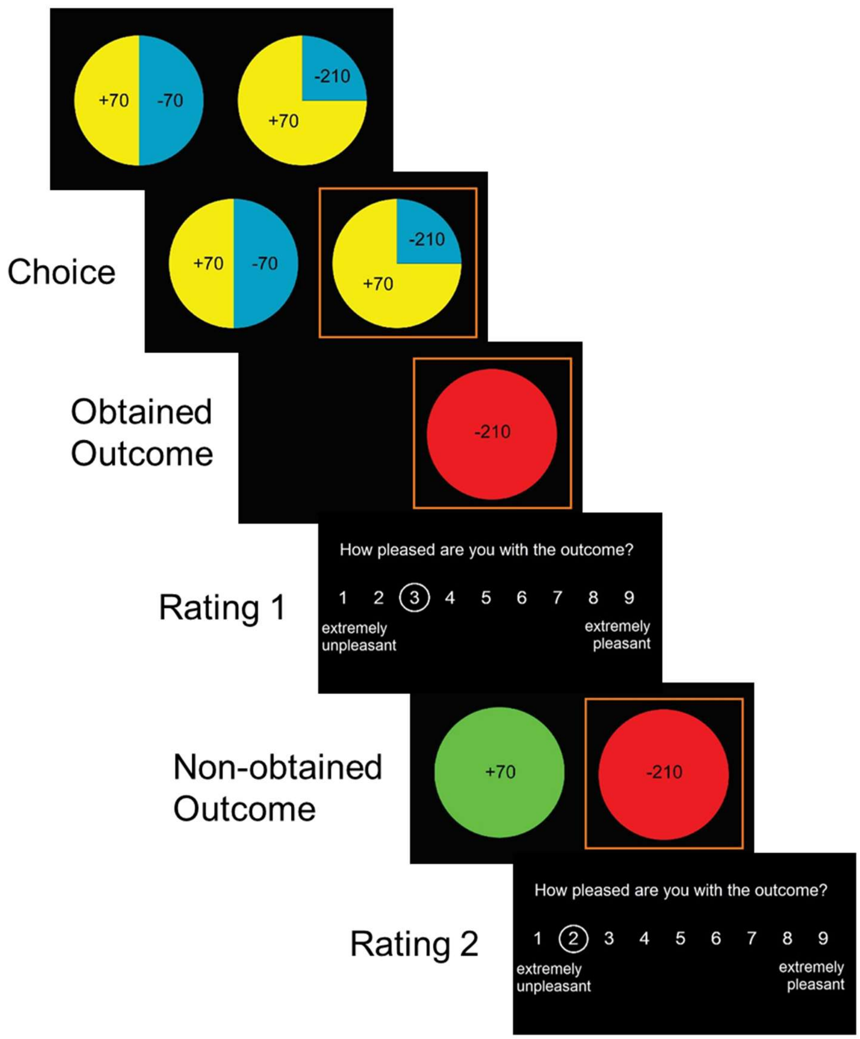


Figure 2. Affect ratings on the regret task as a function of the obtained and counterfactual outcomes: A) affect rating 1 (after presentation of the obtained outcome) as a function of the obtained outcome; B) affect rating 1 as a function of the 'chance counterfactual term', the difference between the obtained outcome and the non-obtained outcome on the chosen wheel; C) affect rating 2 (after presentation of the non-obtained outcome) as a function of the obtained outcome; D) affect rating 2 as a function of the 'agent counterfactual term', the difference between the obtained outcome, and the non-obtained outcome on the other wheel. Red: healthy control group (Con), Blue: group with Gambling Disorder (GD). Shading around lines represents 95% CI for point estimates.

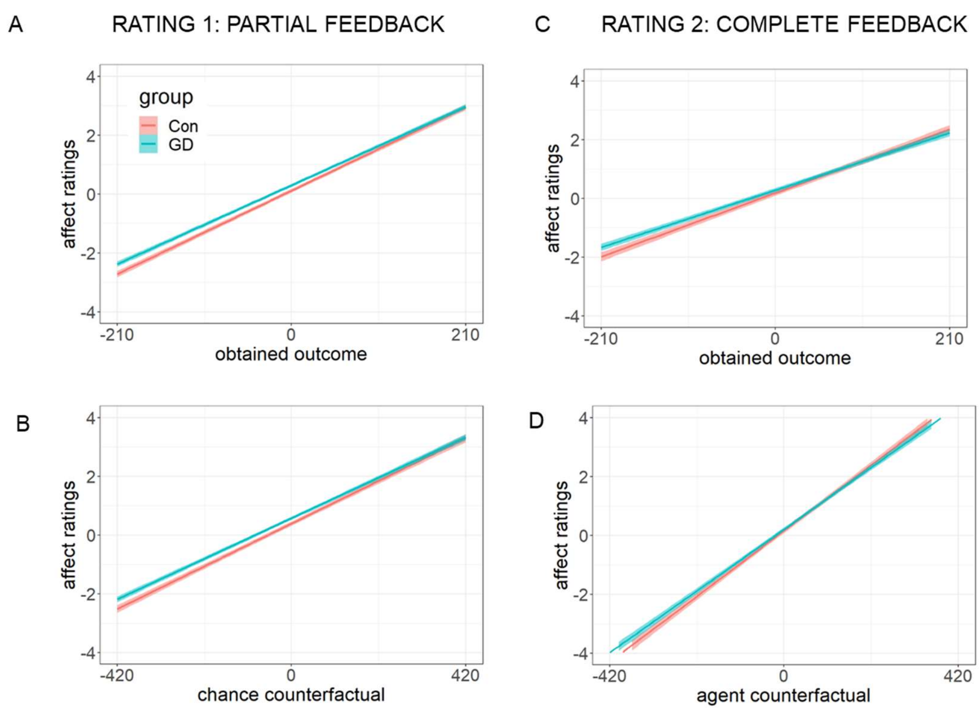
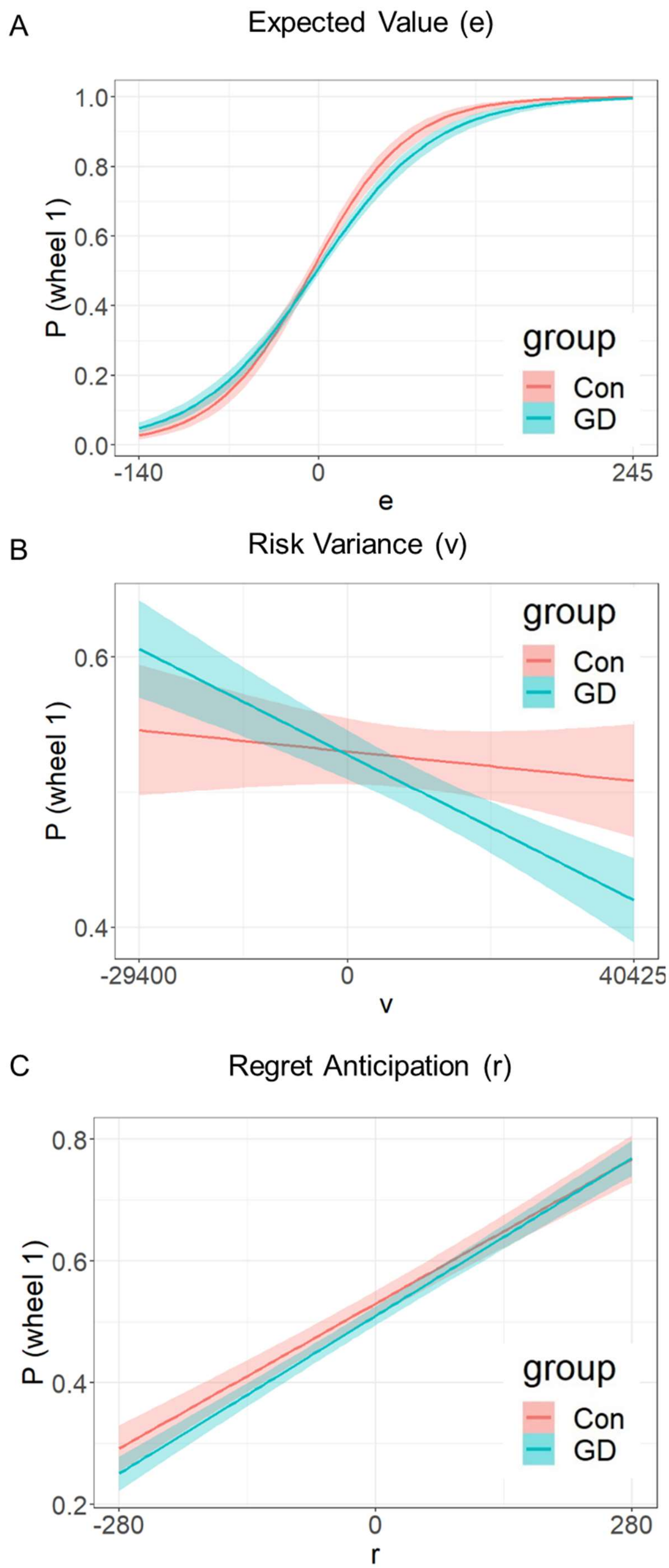


Figure 3. Computational analysis of choice behaviour. The panels indicate the logit-model predicted probability of choosing wheel 1, as a function of A) expected value (e), B) risk variance (v), C) anticipated regret (r). Note: the figures display the unstandardized choice parameters. Red: healthy control group (Con), Blue: group with Gambling Disorder (GD). Shading around lines represents 95% CI for point estimates.


A
Expected Value (e)
P (wheel 1)
1.0
0.8
0.6
0.4
0.2
0.0
-140
0
245
e
group
Con
GD
B
Risk Variance (v)
P (wheel 1)
0.6
0.4
-29400
0
40425
v
group
Con
GD
C
Regret Anticipation (r)
P (wheel 1)
0.8
0.6
0.4
0.2
-280
0
280
r
group
Con
GD

Supplemental Material

"Should've known better": Counterfactual processing in disordered gambling, by Yin Wu, Dawn Kennedy, Caylee-Britt Goshko, Luke Clark

Assessment of other mental health problems

Other mental health problems were assessed using 8 of the 13 domains in the DSM-5 'Cross Cutting Tool' (American Psychiatric Association, 2013), as the SCID-5 Research Version was not released at the time when we started the study. The 8 domains were: depression, anger, mania, anxiety, somatic symptoms, sleep disturbance, repetitive thoughts and behaviours, and substance use (see Table 2). The questions pertain to symptom severity during the past 2 weeks. In each domain, participants who endorsed the level 1 screening items received more extensive questioning (i.e. the level 2 assessment) to ascertain severity. For each domain, we report chi-squared analyses on the number in each group who endorsed the screening item, followed by non-parametric Wilcoxon's rank-sum tests on domain severity in those participants. The Cross Cutting Tool was found to have acceptable internal consistency and validity in adult clinical samples (Bravo, Villarosa-Hurlocker, & Pearson, 2018).

Supplementary Table 1. DSM-5 Cross Cutting measure

		Gambling Disorder (N = 46)	Controls (N = 25)	Statistics
Depression				
	Screen n	31	8	χ^2 = 8.195, p = .004
	Positive	23.35 (6.46)	16.38 (6.39)	U = 53.50, p = .014
Anxiety				
	Screen n	30	13	χ^2 = 1.185, p = .276
	Positive	20.87 (5.37)	16.77 (3.96)	U = 101.00, p = .013
Substance Use				
	Screen n	20	2	χ^2 = 9.534, p = .002
	Positive	4.35 (2.48)	3.5 (3.54)	U = 17.00, p = .728
Mania				
	Screen n	27	10	χ^2 = 2.269, p = 0.132
	Positive	6.07 (3.25)	6.60 (2.95)	U = 121.50, p = .642
Repetitive Thought				
	Screen n	19	2	χ^2= 8.625, p = .003
	Positive	8.74 (3.37)	9.00 (4.24)	U = 16.50, p = .763
Sleep Disturbance				
	Screen n	27	7	χ^2 = 6.115, p = .013
	Positive	29.48 (4.48)	28.00 (3.37)	U = 72.50, p = .347
Somatic Symptoms				
	Screen n	29	6	χ^2 = 9.878, p = .002
	Positive	9.93 (4.61)	5.00 (2.68)	U = 27.00, p = .008
Anger				
	Screen n	27	5	χ^2 = 9.796, p = .002
	Positive	15.26 (2.74)	12.80 (1.64)	U = 30.5, p = .053

Decision Latencies

We tested the influence of expected value, risk variance, anticipated regret, and their interactions with group, on the decision latencies. As each of the three parameters is a difference score that can favour wheel 1 or wheel 2 (see Methods), we inserted the absolute difference scores as predictors, with an expectation that latencies should be slowest on difficult choices where the (absolute) difference between wheels was close to zero. As seen in Supplementary Table 2, the healthy controls (as the reference category) made slower decisions where expected value and risk variance were more similar between the two options; the anticipated regret term was not significant. These parameters did not interact with group in predicting decision latencies.

Supplementary Table 2. Model of decision latencies, based on absolute values for expected value (e), risk variance (v) and anticipated regret (r).

Parameter	Coefficient	SE	95% CI	t value	*p* value
intercept	5976	528.0	4938, 7014	11.32	< .001
e	-8.44	3.13	-14.57, -2.30	-2.70	.007
v	-0.0408	0.0119	-0.064, -0.017	-3.418	<.001
r	0.497	1.47	-2.37, 3.37	0.339	.735
e*group	-3.15	3.89	-10.78, 4.46	-0.811	.417
v*group	0.00263	0.0148	-0.026, 0.032	0.178	.858
r*group	0.253	1.81	-3.29, 3.79	0.140	.889
	71 subjects, 5460 observations. Log Likelihood: -55281.63				

Individual Differences

Sensitivity analyses tested the impact of four covariates: (i) gambling distortions (GRCS) and (ii) problem gambling severity (PGSI) were examined as factors of *a priori* interest, (iii) age was examined given the marginal difference in age between groups, along with evidence for age-related changes in counterfactual thinking (Brassen, Gamer, Peters, Gluth, & Büchel, 2012); (iv) smoking was examined (as a binary variable) given that smoking contributed to group differences in heart rate variability in the same sample (Kennedy et al., 2019). These variables were correlated against the 3 choice model parameters, the rating slopes for the obtained outcome on rating 1, and the agent counterfactual term on rating 2 (see Supplementary Table 3). These tests were restricted to the group with gambling disorder, as the observed group differences could create artefactual associations in the pooled group. Some significant relationships were observed within measures from the regret task; for example, a positive correlation between the *r* choice parameter and the agent counterfactual rating ($r = .326$, $p < .05$). No significant correlations were detected between the task measures and the individual difference covariates.

References

American Psychiatric Association. (2013). Online Assessment Tools. Retrieved from https://www.psychiatry.org/psychiatrists/practice/dsm/educational-resources/assessment-measures

Brassen, S., Gamer, M., Peters, J., Gluth, S., & Büchel, C. (2012). Don't look back in anger! Responsiveness to missed chances in successful and nonsuccessful aging. *Science (New York, N.Y.)*, *336*(6081), 612–614. https://doi.org/10.1126/science.1217516

Bravo, A. J., Villarosa-Hurlocker, M. C., & Pearson, M. R. (2018). College student mental health: an evaluation of the DSM-5 Self-Rated Level 1 Cross-Cutting Symptom Measure. *Psychological Assessment*, *30*(10), 1382–1389. https://doi.org/10.1037/pas0000628

Kennedy, D., Goshko, C.-B., Murch, W. S., Limbrick-Oldfield, E. H., Dunn, B. D., & Clark, L. (2019). Interoception and respiratory sinus arrhythmia in gambling disorder. *Psychophysiology*, (August 2018), e13333. https://doi.org/10.1111/psyp.13333

Supplementary Table 3. Individual differences in the Gambling Disorder group: effects of gambling clinical variables and demographic factors on the choice model parameters (z transformed) and affective ratings

	PGSI	GRCS	Age	Smoking	*e*	*v*	*r*	Rating: Obtained	Rating: Agent CF
PGSI									
GRCS	.173								
Age	.056	-.315*							
Smoking	.266	-.203	-.034						
e	-.178	.191	-.275	-.225					
v	.000	-.145	.229	.113	0.11				
r	-.258	-.19	.032	-.051	.318*	.090			
Rating: Obtained	-.001	.235	-.007	-.177	.333*	.106	.147		
Rating: Agent CF	-.132	-.092	-.101	.045	.392*	.161	.327*	.712**	

* $p < .05$ ** $p < .005$. PGSI = Problem Gambling Severity Index, GRCS = Gambling Related Cognitions Scale

Supplementary Table 4.Trial sequence: gamble options on Wheel 1 and 2, and derived model parameters for e, v and r

	Wheel 1					Wheel 2					Model Parameters		
trial	x1	p	y1	1-p	Outcome	x2	q	y2	1-q	Outcome	e	v	r
1	70	0.75	-210	0.25	70	210	0.25	-70	0.75	-70	0	0	-280
2	70	0.5	-70	0.5	70	210	0.5	-210	0.5	210	0	39200	0
3	210	0.25	-70	0.75	-70	210	0.5	-210	0.5	-210	0	29400	140
4	70	0.5	-210	0.5	70	70	0.25	-70	0.75	-70	-35	-15925	-140
5	70	0.75	-70	0.25	70	210	0.5	-70	0.5	210	-35	15925	-140
6	70	0.5	-70	0.5	-70	210	0.5	-210	0.5	210	0	39200	0
7	210	0.25	70	0.75	210	210	0.5	-70	0.5	-70	35	15925	140
8	210	0.5	70	0.5	210	210	0.75	-210	0.25	210	35	28175	280
9	70	0.75	-210	0.25	70	210	0.5	-210	0.5	-210	0	29400	-140
10	70	0.75	-210	0.25	70	210	0.5	-210	0.5	-210	0	29400	-140
11	210	0.25	-70	0.75	210	70	0.5	-70	0.5	-70	0	-9800	140
12	70	0.75	-70	0.25	-70	210	0.25	70	0.75	70	-70	0	-280
13	-70	0.5	-210	0.5	-210	210	0.25	-210	0.75	210	-35	28175	-280
14	210	0.25	70	0.75	210	210	0.5	-70	0.5	210	35	15925	140
15	210	0.25	-210	0.75	210	-70	0.75	-210	0.25	-70	0	-29400	280
16	-70	0.5	-210	0.5	-210	70	0.25	-210	0.75	70	0	9800	-140
17	-70	0.5	-210	0.5	-210	70	0.25	-210	0.75	-210	0	9800	-140
18	70	0.75	-210	0.25	-210	210	0.25	-70	0.75	210	0	0	-280
19	-70	0.75	-210	0.25	-70	210	0.25	-210	0.75	-210	0	29400	-280
20	210	0.5	70	0.5	70	210	0.75	-210	0.25	210	35	28175	280
21	70	0.5	-210	0.5	-210	70	0.25	-70	0.75	-70	-35	-15925	-140
22	70	0.5	-70	0.5	70	70	0.75	-210	0.25	70	0	9800	140
23	70	0.75	-70	0.25	70	70	0.75	-70	0.25	-70	0	0	0

	Wheel 1					Wheel 2					Model Parameters		
trial	x1	p	y1	1-p	Outcome	x2	q	y2	1-q	Outcome	e	v	r
24	210	0.5	-210	0.5	210	210	0.25	-210	0.75	210	105	-11025	0
25	210	0.25	-70	0.75	-70	70	0.5	-70	0.5	70	0	-9800	140
26	70	0.5	-70	0.5	70	70	0.75	-210	0.25	70	0	9800	140
27	210	0.25	70	0.75	70	210	0.75	-210	0.25	210	0	29400	280
28	210	0.5	70	0.5	210	210	0.75	-70	0.25	210	0	9800	140
29	70	0.75	-210	0.25	70	210	0.25	-70	0.75	-70	0	0	-280
30	70	0.5	-70	0.5	70	210	0.25	-70	0.75	-70	0	9800	-140
31	210	0.75	-210	0.25	-210	70	0.25	-210	0.75	-210	245	-18375	140
32	210	0.5	70	0.5	70	210	0.75	-70	0.25	-70	0	9800	140
33	70	0.75	-210	0.25	70	210	0.25	-70	0.75	-70	0	0	-280
34	70	0.75	-70	0.25	70	210	0.5	-210	0.5	210	35	40425	0
35	70	0.5	-210	0.5	-210	70	0.25	-70	0.75	70	-35	-15925	-140
36	-70	0.5	-210	0.5	-70	210	0.25	-210	0.75	-210	-35	28175	-280
37	70	0.75	-70	0.25	-70	210	0.25	-70	0.75	-70	35	11025	-140
38	70	0.25	-210	0.75	-210	-70	0.5	-210	0.5	-70	0	-9800	140
39	70	0.5	-70	0.5	70	70	0.75	-210	0.25	-210	0	9800	140
40	70	0.5	-70	0.5	-70	210	0.25	-70	0.75	-70	0	9800	-140
41	210	0.5	-210	0.5	-210	210	0.25	-210	0.75	-210	105	-11025	0
42	210	0.25	-70	0.75	-70	210	0.5	-210	0.5	210	0	29400	140
43	70	0.75	-70	0.25	70	210	0.5	-70	0.5	-70	-35	15925	-140
44	210	0.25	-210	0.75	210	70	0.5	-210	0.5	70	-35	-13475	140
45	210	0.25	-210	0.75	-210	70	0.5	-210	0.5	-210	-35	-13475	140
46	-70	0.75	-210	0.25	-70	210	0.5	-210	0.5	210	-105	40425	-280
47	-70	0.5	-210	0.5	-70	70	0.25	-210	0.75	-210	0	9800	-140

	Wheel 1					Wheel 2					Model Parameters		
trial	x1	p	y1	1-p	Outcome	x2	q	y2	1-q	Outcome	e	v	r
48	210	0.5	70	0.5	70	210	0.75	-70	0.25	-70	0	9800	140
49	210	0.5	70	0.5	210	210	0.75	-70	0.25	-70	0	9800	140
50	210	0.5	-210	0.5	-210	210	0.25	-70	0.75	-70	0	-29400	-140
51	210	0.5	-210	0.5	-210	70	0.25	-210	0.75	-210	140	-29400	140
52	70	0.75	-70	0.25	70	210	0.5	-70	0.5	210	-35	15925	-140
53	210	0.25	70	0.75	70	210	0.5	-70	0.5	210	35	15925	140
54	210	0.5	-70	0.5	-70	210	0.75	-210	0.25	-210	-35	13475	140
55	70	0.75	-210	0.25	-210	210	0.25	-70	0.75	-70	0	0	-280
56	-70	0.75	-210	0.25	-70	210	0.25	-210	0.75	-210	0	29400	-280
57	70	0.5	-70	0.5	-70	70	0.75	-210	0.25	70	0	9800	140
58	70	0.75	-210	0.25	-210	70	0.25	-70	0.75	-70	35	-11025	-140
59	210	0.25	-210	0.75	-210	-70	0.5	-210	0.5	-70	35	-28175	280
60	210	0.75	-210	0.25	210	210	0.25	70	0.75	210	0	-29400	-280
61	210	0.5	70	0.5	210	210	0.75	-210	0.25	-210	35	28175	280
62	210	0.25	-210	0.75	-210	210	0.25	-210	0.75	-210	0	0	0
63	70	0.5	-210	0.5	70	70	0.25	-70	0.75	-70	-35	-15925	-140
64	210	0.25	70	0.75	70	210	0.75	-210	0.25	210	0	29400	280
65	70	0.75	-70	0.25	-70	210	0.5	-70	0.5	-70	-35	15925	-140
66	210	0.25	-210	0.75	210	70	0.75	-70	0.25	-70	-140	-29400	0
67	210	0.5	70	0.5	210	210	0.5	-210	0.5	-210	140	39200	280
68	210	0.25	70	0.75	210	210	0.5	-70	0.5	210	35	15925	140
69	70	0.25	-210	0.75	70	70	0.5	-210	0.5	70	-70	4900	0
70	-70	0.5	-210	0.5	-210	210	0.25	-210	0.75	-210	-35	28175	-280
71	70	0.5	-70	0.5	70	210	0.75	-210	0.25	210	-105	28175	0

	Wheel 1					Wheel 2					Model Parameters		
trial	x1	p	y1	1-p	Outcome	x2	q	y2	1-q	Outcome	e	v	r
72	210	0.25	-70	0.75	-70	210	0.5	-210	0.5	210	0	29400	140
73	70	0.75	-210	0.25	-210	210	0.5	-210	0.5	210	0	29400	-140
74	210	0.5	70	0.5	70	210	0.75	-210	0.25	210	35	28175	280
75	210	0.25	70	0.75	70	210	0.75	-210	0.25	210	0	29400	280
76	210	0.75	-210	0.25	210	210	0.5	-70	0.5	210	35	-13475	-140
77	210	0.5	-210	0.5	210	210	0.75	-210	0.25	210	-105	-11025	0
78	70	0.5	-70	0.5	-70	210	0.5	-210	0.5	-210	0	39200	0