RESEARCH ARTICLE

REVISED Experience of regret is unaffected by concurrent working memory load

[version 2; peer review: 2 approved]

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Abstract

Background

When facing the consequences of decisions, people often experience evaluative emotions such as regret. The experience of regret is the result of the comparison between the actual outcome of one's actions and a better counterfactual outcome that could have occurred had one acted differently in the past. Despite increasing interest in counterfactual thinking and regret, little is known about the type of cognitive processes involved with regret –whether it is underpinned by reflective or intuitive processes. The extant literature provides contradictory evidence: theoretical assertions and developmental work point towards reflective processes, requiring access to capacity-limited cognitive resources whereas, some experimental and neuroscientific evidence point towards intuitive processes.

Methods

In the current study, adults (N = 20) completed a commonly used gambling task known to elicit regret under high or low working memory load.

Results

Ratings of regret were not affected by concurrent working memory load (Bayes Factors provided strong evidence for the null hypothesis).

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Conclusions

We conclude that the experience of regret in a commonly used gambling task is unaffected by concurrent working memory load. This suggests that, in adults, regret is not always reliant on reflective cognitive processes and does not require access to central cognitive resources.

Keywords
regret, counterfactual thinking, working memory, reflective, intuitive, dual task

This article is included in the Counterfactual Thinking collection.

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REVISED **Amendments from Version 1**

In this updated version of the manuscript, we have (1) clarified the theoretical underpinnings of the research, (2) included some additional information about the task setup and outcome frequencies, (3) extended the discussion by considering further explanations and implications of the findings, and (4) signposted to new supplementary analysis file that includes an additional figure and further exploration of the amplification effect and effects of experience.

Any further responses from the reviewers can be found at the end of the article

Introduction

When facing the consequences of decisions, people often experience evaluative emotions such as satisfaction, disappointment, relief, or regret. For example, I might experience regret when I get caught in the rain without an umbrella. The experience of regret is the result of the comparison between the actual outcome (getting soaking wet in a rainstorm) and a better counterfactual outcome that would have happened had I acted differently at some point in the past (remembering to pack an umbrella; Loomes & Sugden, 1982). In this sense, the experience of regret relies on counterfactual thinking – thinking about what might have been. Although there is a great deal of interest in regret, fundamental understanding of the processes underpinning this complex emotion is still lacking. Specifically, the literature provides apparently contradictory evidence as to whether the experience of regret relies on high-level reflective processes that require access to central, capacity-limited cognitive resources. In this paper we further explore this question and present evidence that the experience of regret in a commonly used gambling paradigm is unaffected by concurrent demands on central cognitive resources.

Definitions of regret often imply that it relies on reflective reasoning, specifically counterfactual, or "what if" thinking. For example, van Dijk and Zeelenberg (2005, p. 152) define regret as "a negative emotion that we experience when we realize or imagine that our present situation would have been better, if only we had decided differently". This comparison between the current situation and a more positive counterfactual outcome arising from a different past action or decision is the defining feature of regret and differentiates it from disappointment. Regret requires thinking about what, hypothetically, might have been had one acted differently in the past and so it is plausible to assume that regret requires reflective processes to simulate these hypothetical situations. Indeed, Evans and Stanovich (2013) make a distinction between 'basic' and 'complex' emotions, placing basic emotions with intuitive processes, and complex emotions, including regret, with reflective processes. By contrast, the evaluative emotion disappointment is associated with comparison between an actual outcome and a better alternative, but does not require consideration or simulation of the connection between one's own decisions and the actual and counterfactual outcomes (Zeelenberg *et al.*, 1998).

Many psychologists believe that human cognition is broadly reliant on two types of cognitive processes – intuitive and reflective processes (Evans, 2008; Evans & Stanovich, 2013; Kahneman, 2012). This distinction is useful in considering what kind of cognitive processes are required for the experience of regret. Intuitive processes are fast and automatic, and do not rely on central cognitive resources. By contrast, reflective processes require access to limited capacity cognitive resources to perform mental simulation of hypothetical events. Reading words on a billboard can be fast and automatic, while engaging with a complex text to comprehend its argument requires reflective processes (Kahneman, 2012). For example, in the domain of theory of mind, researchers have proposed a dual-systems account of perspective taking. According to this account, fast, automatic, intuitive processes allow individuals to process what is or is not seen by others, while reflective, cognitively costly, flexible processes permit more complex perspective taking including the way someone sees an object (Low *et al.*, 2016). Dual-systems accounts have recently been challenged by De Neys (2021), who questions whether a dichotomy between two distinct ways of thinking is supported by evidence or even testable. With this in mind, although we acknowledge that dual-systems approaches have guided our thinking on the processes involved in counterfactual thinking, our current question does not require commitment to either the view that intuitive and reflective processes are qualitatively distinct from each other or that they are aspects of a single continuum. Furthermore, the empirical evidence we present in this paper does not speak to this issue. Aside from theories of reasoning, other fields of research have contributed to our question of whether regret requires high-level reflective thinking. One is the claim that regret develops relatively late in childhood. Recruitment of reflective cognitive processes is considered to be related to a child's age and cognitive ability (Evans, 2011), thus cognitive functions that rely on these reflective processes are thought to emerge later than those relying only on intuitive processes (Low *et al.*, 2016). In tasks designed to elicit regret in young children, they typically learn that although their decision led to some small quantity of sweets or stickers, they could have had considerably more if they had chosen differently. Children are at least 5 or 6 years old before they reliably report experiencing regret (O'Connor *et al.*, 2014; Weisberg & Beck, 2010) and some claim that the emotion is not experienced until much later (Rafetseder & Perner, 2012). Furthermore, developmental individual differences studies report that counterfactual thinking and the experience of regret are predicted by children's executive functions (i.e. central cognitive resources; see Beck *et al.*, 2009; Burns *et al.*, 2012). On the other hand, other authors interpret their evidence to suggest that children can think counterfactually from a young age, before 3 (Buchsbaum *et al.*, 2012), which could be extended to suggest that counterfactual thinking and perhaps regret does not rely on reflective thinking.

Complementary to this latter position, is evidence from neuroimaging that raises doubt over whether regret requires reflective processes: in adults, the neural signature relating to regret arises extremely fast, suggesting intuitive processing.

Giorgetta *et al.* (2013) used a gambling paradigm (adapted from Mellers *et al.*, 1997) that was similar to the one that we will use in this study. Participants played a gambling game involving two wheels of fortune; each wheel offered two different amounts of points with the outcome of each wheel determined by a spinner. Participants chose a wheel and received the outcome of that wheel. Regret was induced in trials where participants chose the wheel and their wheel resulted in a loss while the rejected wheel would have led to a gain. Disappointment trials had the same outcomes, but the choice of wheel was determined by the computer. Magnetoencephalography (MEG) results indicated that the regret and disappointment trials were differentiated extremely fast at the neural level (between 190 and 305ms). This suggests that the key information about the participant's choice informed the affective response very early, in line with the idea that regret results from fast and intuitive processes. However, this evidence concerns differentiation in neural processes, not in people's actual experience of the emotion, leaving open the question of whether regret can occur without reflective processes.

Perhaps the strongest evidence for intuitive processing in counterfactual thought comes from a study of counterfactual thinking with a concurrent working memory load. Goldinger, Kleider, Azuma and Beike (2003) made the strong claim that counterfactual thinking happens automatically, based on evidence that it is effortful for people to suppress counterfactuals, but not to generate them. In this study, participants made judgements of situations in which there was a more or less salient counterfactual alternative. For example, in one experiment, participants decided how much compensation to award a victim who was at a baseball game when he was injured by a falling light fitting. In one version of the story the protagonist was sat in his usual seat and in the other he had purposely moved to a different seat. In the latter case, the counterfactual "If only he hadn't changed seats" is likely to be available and indeed, participants assigned more blame (and less compensation) to the victim in this version.

Importantly, when participants with lower working memory span held a further memory load during the judgment stage of the task, their judgments suggested that they were more influenced by the counterfactual alternative than participants in other conditions: They attributed more blame to the victim and recommended less compensation. By contrast, holding a memory load while reading the story (encoding) had little effect on their judgements. The authors interpreted these results as suggesting that counterfactuals are automatically produced during the encoding stage and need effortful suppression when making judgments. In other words, this evidence suggests that counterfactual thinking is quick and effortless, an intuitive process. It remains possible, however, that even if the underlying counterfactuals are generated automatically, the emotion of regret, which requires comparison between the counterfactual and reality, may require reflective processes. Indeed, when ascribing regret to others, performance can be disrupted by being required to make speeded responses (Atkinson *et al.*, 2009).

There is a tension in the literature as regret seems to possess core features of both reflective and intuitive reasoning. This tension is evident even within some of the key articles on regret and counterfactual thinking more generally. For example, in Camille *et al.*'s (2004) important paper on the neurological basis of regret, they emphasize the cognitive nature of regret but also suggest that the counterfactuals, on which regrets are based, are evoked automatically, in reference to Kahneman and Miller's (1986) norm theory. Similarly, Ferguson's extensive work on counterfactual inferences suggests that people have rapid access to counterfactual possibilities, but also that inferences based on counterfactuals may be more effortful than those based on reality (Ferguson, 2012; Ferguson & Sanford, 2008). Roese, Sanna, and Galinsky (2005) consider the possibility that people might generate upward counterfactuals (how things could have been better) intuitively, but downward counterfactuals (how things could have been worse) require reflective processing, and that all counterfactuals can be controlled or suppressed after generation.

There have been many attempts to operationalize reflective and intuitive processes, resulting in an extensive list of characteristics. However, Evans (2008, p. 220) suggests that the key difference between them is that reflective processes require access to limited-capacity central resources, while intuitive processes do not require such access. That regret fundamentally involves such limited capacity resources is consistent with Redshaw and Suddendorf's (2020) analysis of the representational resources required for different types of thought about possibility, which they suggest can be classed in terms of a hierarchy of difficulty. Specifically, Redshaw and Suddendorf (2020) argue that regret requires working memory capacity because it involves what they term temporal embedding: it involves thinking backwards in time to a point at which there were still various possible ways the future could unfold, simulating an alternative past, and then comparing the outcome of the simulation to the actual present state of affairs. Somewhat surprisingly, though, despite the interest in the processes underpinning regret, there have been few investigations of the relation with central resources such as working memory. Developmental research has shown that children's competence on counterfactual thinking tasks is sometimes predicted by working memory (Guajardo *et al.*, 2009; but not always, see Beck *et al.*, 2009; Burns *et al.*, 2012), although this may be due to the heavy verbal demands in the task and the need to generate multiple counterfactual alternatives. Indeed, Burns *et al.* (2012) found no relationship between children's working memory ability and their tendency to experience regret. The demands of counterfactual thinking in adults are often discussed in terms of working memory (Byrne, 2002; Byrne & McEleney, 1997; Ferguson & Cane, 2015), but to our knowledge there have been no direct tests of the role of working memory in adults' experience of regret. Returning to the debate set up by De Neys (2021), knowing whether regret makes demands on working memory does not tell us whether there is a dual- or single- system of reasoning in place. But it does tell us whether regret draws on limit-capacity resources and should be characterised as a (relatively) reflective process.

Since working memory load places demands on limited-capacity central resources (Bunge *et al.*, 2000), one common strategy to determine the kind of processing required for a cognitive function is then to use a concurrent working memory task and assess disruption to the function of interest (e.g., Hinson *et al.*, 2003). This technique has not yet been utilized to better understand regret, although deception has been shown to be disrupted by concurrent working memory demands (Van 't Veer *et al.*, 2013), and is also related to counterfactual thinking (Briazu *et al.*, 2017).

In the current study, we asked participants to complete a regret-inducing gambling task (Camille *et al.*, 2004; Mellers *et al.*, 1997), while also loading their working memory. Participants chose between two wheels of fortune each offering different gambles. In 'partial' trials, participants only saw the outcome of the chosen wheel, exposing them to the obtained outcome, and the outcome they missed by chance. In 'complete' trials, participants saw the outcomes of both the chosen and rejected wheels, exposing them to the outcome they rejected, and so the possibility of regret. Participants then rated their emotional experience. Participants were judged to experience regret when their emotion ratings were moderated not only by the outcome of the chosen wheel, but also by the outcome of the rejected wheel – i.e. they felt worse on complete trials after learning about better rejected outcomes.

Adopting a dual task methodology allowed us to examine whether the experience of regret relies on reflective processes (Hinson *et al.*, 2003). Participants had to hold in mind a number string while observing the outcomes of the wheels and making their emotional rating. In the low load condition participants had only 2 digits to remember, but in the high load condition the number string was 5 digits long. We predicted that if regret relies on reflective processes, then a high working memory load would reduce the impact of the rejected outcome on emotion ratings, while the effects of the obtained outcome and the outcome missed by chance (leading to disappointment) would be expected to remain intact. By contrast, if regret does not rely on reflective processes, then a high working memory load would make little or no difference to the impact of the rejected outcome on emotion ratings.

Method

Participants

A total of 20 female participants aged between 18 and 25 (M = 19.4 years) participated in the study. All participants were undergraduate students at the University of Birmingham recruited via the School of Psychology's research participation scheme in return for course credits. No further rewards were given based on task performance. No inclusion or exclusion criteria were used – all students enrolled in the School of Psychology's research participation scheme were eligible to take part. One participant did not provide data due to a technical issue with the task that was amended prior to continuation of data collection. The sample size was based on previous studies from the neuropsychological literature (Bault *et al.*, 2019; Camille *et al.*, 2004; Coricelli *et al.*, 2005). A sensitivity analysis using the 'simr' package in R (Green & MacLeod, 2016) with 300 runs showed that our design had 100% power to detect the effect of working memory load on regret if it was as large as the between-group effect of lesions to the ventromedial prefrontal cortex in a similar task that used a similar approach to the analysis (Bault *et al.*, 2019), and 87% power to detect an effect half as large.

Ethical considerations

The study received ethical approval from the University of Birmingham Ethical Review Committee under the Social and Behavioural Studies with Adults programme (ERN_09-719, 2009). All participants provided written informed consent prior to participation.

Procedure

The experiment took place at the University of Birmingham in October 2015. The experiment was administered on a Toshiba 15" laptop and run on PsychoPy, version 1.73.04 (Peirce, 2007; Peirce *et al.*, 2011). Full experimental materials are available in the supplementary materials (https://doi.org/10.17605/OSF.IO/N28BU). The experiment had two blocks of 60 trials, and an additional 6 practice trials. Working memory load (low and high) was varied between blocks and the order of load conditions counterbalanced between participants. Before the experiment, participants completed two practice trials without the working memory load, one partial trial and one complete trial and were asked to rate their emotional response to the outcome. Prior to each block participants also received two practice trials to introduce the working memory load manipulation for the upcoming block.

On each trial, participants were presented with two wheels of fortune (see Figure 1). Each wheel had two possible outcomes from {-200, -50, 50, 200} and the probabilities of each outcome were either both .5, or .2 and .8, depicted by the proportion of the wheels coloured red and blue (see the supplementary materials for the trial list; https://doi.org/10.17605/OSF.IO/N28BU). Participants chose a wheel and then received either partial feedback (only the outcome of the chosen wheel was revealed by an arrow pointing to one portion of the chosen wheel) or complete feedback (the outcomes of both wheels were revealed by arrows pointing to portions of the chosen and rejected wheels) for 2 seconds. Participants observed the 'obtained outcome' – where the arrow landed on the chosen gamble, and the 'missed outcome' – where the arrow did not land on the chosen wheel in both partial and complete trials. In complete trials, participants additionally observed the 'rejected outcome' (where the arrow landed in the rejected wheel). Participants then rated their emotions on a visual analogue scale (coded from -50 to 50). The trials were presented in a pseudorandomised order with equal proportions of partial and complete feedback trials. Participants had genuine choice about their selection of the gamble wheels, so each participant will have faced different combinations of outcomes across the trials. On average, participants received outcomes of -200 on 6% of trials, -50 on 31% of trials, 50 on 48% of trials, and 200 on 14%

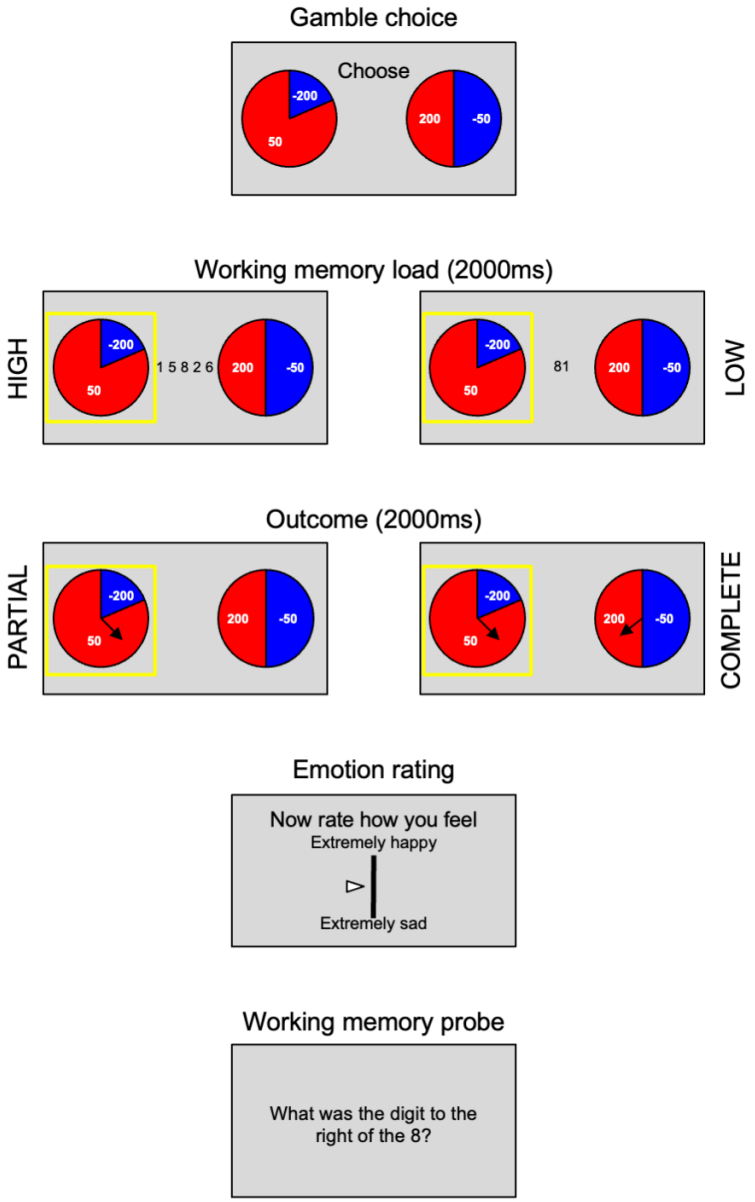

Figure 1. Trial structure. Participants first choose between two monetary gambles. They are then presented with a string of 2 (low load condition) or 5 (high load condition) digits for 2000ms. They then see the outcome of the chosen wheel (partial trials) or the chosen and rejected wheels (complete trials) for 2000ms before rating their emotions on a visual analogue scale. Finally, participants unload working memory by reporting the digit to the right of the probed digit (in the figure, this would be 2 in the high load condition and 1 in the low load condition). In the example trials depicted in this figure, the 'obtained outcome' is the red portion of the chosen (left) wheel. The 'missed outcome' is the blue portion of the chosen wheel. The 'rejected outcome' is the red portion of the rejected (right) wheel in the complete (right) trial.

of trials. Participants 'won' the trial by obtaining a better outcome than the rejected and/or missed outcome on 51% of trials. Participants were not shown the accumulation of points across the task and points were not translated into any extrinsic rewards after participation.

Working memory was 'loaded' on each trial after participants chose a wheel and 'unloaded' after they made their emotion ratings, thus they observed the gamble outcomes and rated their emotion under load. A string of two (low load) or five digits (high load) were randomly selected without replacement from the digits 1 to 9 and displayed between the two wheels for 2 seconds. After rating their emotions, participants were shown a single digit from the string and reported the digit that was to its right in the string. In the low load condition, the probed digit was always the left of the two digits, so

the participant only needed to maintain the right digit while observing the outcomes and rating emotions. In the high-load condition, the probed digit could have been any of the four left-most digits, so participants needed to maintain all five digits in the correct order while observing the outcomes and rating their emotions. Memory accuracy was high for both conditions (low load: M = 94.5%, SD = 5.0%; high load: M = 92.4%, SD = 7.2%), suggesting that participants maintained the load through the exposure to the gamble outcomes. Mixed-effects models revealed significant effects of load condition on both accuracy (p = .034) and response time (low load: M = 1102ms, SD = 238ms; high load: M = 1896ms, SD = 354ms; p < .001) for the responses to the working memory probe, suggesting that the high load manipulation was more cognitively demanding than the low load condition.

Data analysis

We analysed the data from partial and complete trials separately using linear mixed-effects models predicting emotion rating responses. Each included the working memory load condition (Load; coded as -0.5 = low load; 0.5 = high load), the value of the obtained outcome (Obtained), the unobtained outcome on the chosen wheel (Missed), and for complete trials, the outcome of the rejected wheel (Rejected) as predictors. Interactions between Load and the three outcome predictors were also included in the model. The models included random intercepts and maximally specified random slopes for participants. To aid model convergence, model complexity was reduced by forcing the correlation parameters of the random effects to zero (Matuschek *et al.*, 2017). Nonetheless, the partial trials model resulted in a singular fit error. Removing the problematic random slope (Obtained*Load) did not modify the fixed effects parameter estimates, so the results of the fully specified model are reported.

In addition to the linear models, a Bayesian approach was taken to determine whether our data provided evidence for an effect of each factor and interaction using the 'brms' package in R. Weak, uninformed priors were generated using the 'auto_prior' function from the 'sjstats' package in R (Lüdecke & Lüdecke, 2017). These priors are normally distributed around a mean of 0 with a standard deviation of 2.5 times the standard deviation of the related variable. Parameters from the mixed-effects models of partial and complete trials and corresponding Bayes Factors (BF_{01}) in support of the null hypothesis (calculated using the Savage Dickey method, see Wagenmakers *et al.*, 2010) are reported in Table 1. Note that BF_{01}s greater than 3 provide positive evidence and greater than 20 provide strong evidence for the null hypothesis, and conversely less than 0.3 provide positive evidence and less than 0.05 provide strong evidence for the alternative hypothesis (see Kass & Raftery, 1995). The analysis script is provided in the supplementary materials along with the raw data (https://doi.org/10.17605/OSF.IO/N28BU).

Results

All participants who provided data were included in the analysis. One participant did not provide data due to a technical issue with the task that was amended prior to further participation (FitzGibbon *et al.*, 2024). The mixed-effects models and Bayesian analysis suggested that neither working memory alone, nor any of the interactions between load and the trial outcomes had significant effects on participants' emotion ratings (see Table 1). The BF_{01}s provided positive or strong evidence for the null hypothesis for all of these predictors (all BF_{01}s < 10). In particular, the interaction between working memory and the rejected outcome (the effect of regret) was not significant, β = -0.01 [-0.11, 0.08], t = -0.29, p = .773, and the BF provides strong evidence for the null hypothesis, BF_{01} = 59.46. These results suggest that manipulation of concurrent working memory load does not disrupt processing of alternative outcomes and their emotional appraisal. If the experience of regret required access to working memory resources, we would have expected a diminished effect of the rejected outcome on emotion ratings – the red and blue lines to be closer together under high load. Observing the summary

Table 1. Parameter estimates from linear mixed effects model and Bayes Factors from equivalent Bayesian mixed effects models.

	Partial					Complete				
	β	CI	t	p	BF_{01}	β	CI	t	p	BF_{01}
Obtained outcome (O)	1.21	1.04 – 1.38	13.98	<.001	<0.001	1.17	0.99 – 1.35	12.57	<.001	<0.001
Missed outcome (M)	-0.40	-0.52 – -0.29	-6.93	<.001	<0.001	-0.27	-0.34 – -0.20	-7.38	<.001	<0.001
Rejected outcome (R)						-0.43	-0.59 – -0.26	-5.11	<.001	<0.001
Load condition (L)	-0.10	-1.53 – 1.32	-0.14	.887	133.2	-0.56	-2.44 – 1.32	-0.59	.565	85.07
O*L	-0.12	-0.24 – 0.01	-1.86	.063	16.76	-0.03	-0.22 – 0.16	-0.31	.757	52.47
M*L	0.05	-0.06 – 0.16	0.83	.416	35.03	0.00	-0.10 – 0.10	0.09	.931	64.96
R*L						-0.01	-0.11 – 0.08	-0.29	.773	59.46

Note. BF_{01} provides a measure of evidence in favour of the null hypothesis that the parameter estimate is equal to zero.

data in the lower panel of Figure 2, it is clear that participants were just as affected by the rejected outcome in the high load condition as in the low load condition.

In contrast, the main effects of the three different outcomes (obtained, missed, and rejected) replicated the patterns of emotion ratings observed in previous research, and Bayes factors provide strong evidence for the effect of each outcome (see Table 1; Bault *et al.*, 2019; Camille *et al.*, 2004; Coricelli *et al.*, 2005). Participants reported more positive emotions when the obtained outcome was greater in both partial trials, β = 1.21 [1.04, 1.38], t = 13.98, p < .001, BF_{01} < 0.001, and complete trials, β = 1.17 [0.99, 1.35], t = 12.57, p < .001, BF_{01} < 0.001. There was a negative effect of the missed outcome on the chosen wheel on partial, β = -0.40 [-0.52, -0.29], t = -6.93, p < .001, BF_{01} < 0.001 and complete trials β = -0.27 [-0.34, -0.20], t = -7.38, p < .001, BF_{01} < 0.001. There was also a negative effect of the outcome of the rejected wheel on complete trials, β = -0.43 [-0.59, -0.26], t = -5.11, p < .001, BF_{01} < 0.001. Participants thus experienced both disappointment and regret during the task – the larger the missed or rejected outcome, the worse participants felt.

Bayesian hypothesis testing also allowed us to test the amplification effect – that participants are more affected by outcomes that they rejected than by outcomes that they missed by chance. Comparison of the effect of the rejected and missed outcomes on complete trials provides positive evidence for this amplification effect – participants were more affected by the outcome that was rejected (β = -0.43) than by the outcome that was missed by chance (β = -0.27), BF_{01} = 0.06. The amplification effect is explored in greater detail in the supplementary analyses (https://doi.org/10.17605/OSF.IO/N28BU).

Discussion

We found no evidence that people's reporting of regret was affected by concurrent working memory load. Across the high and low working memory conditions, we replicated findings from the extant literature by demonstrating that people's emotion ratings were positively associated with the obtained outcome – they felt better when they won more; and negatively associated with both the missed outcome (disappointment), and the rejected outcome (regret) – they felt worse when they could have won more. However, we found no evidence that these effects were attenuated by a concurrent working memory load. People's reported regret was just as great when they had a high concurrent working memory load as when they had a low concurrent load. Reporting regret in a commonly used regret elicitation paradigm apparently does not require working memory, suggesting that regret may not always be reliant on reflective cognitive processes.

How can this be? Regret is conceptualized as a negative emotional response resulting from the comparison between an actual and a counterfactual outcome (Burns *et al.*, 2012; Loomes & Sugden, 1982). It has been assumed that the status of the counterfactual outcome must be determined by simulating a hypothetical alternative course of action – an effortful process relying on limited capacity executive resources. We now

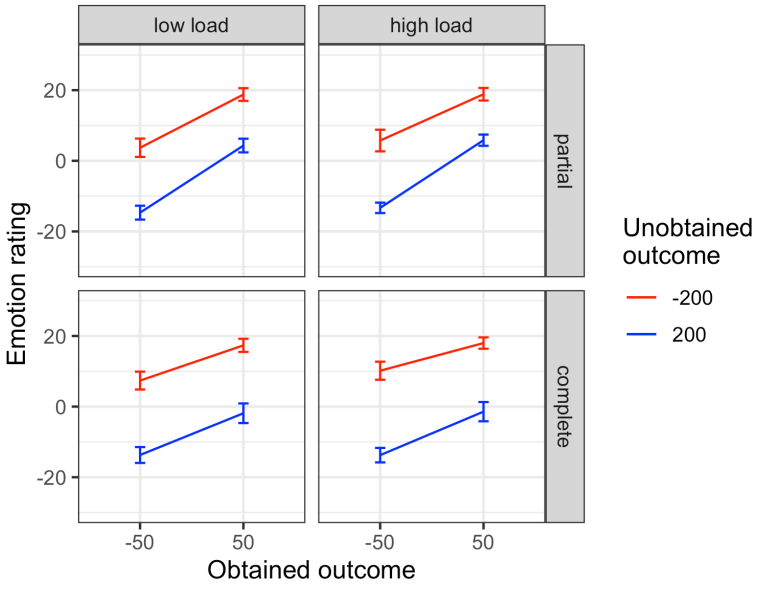

Figure 2. Mean emotion ratings. The slope of the lines represents the effect of the obtained outcome. The difference between red and blue lines represents the effect of the unobtained outcome. The upper panels show partial trials, for which the unobtained outcome is the missed outcome. The lower panels show complete trials, for which the unobtained outcome is the rejected outcome. The left panels show results in the low load condition and the right panels show results in the high load condition. For ease of comparison with previous research (e.g., Camille *et al.*, 2004; Coricelli *et al.*, 2005), the figure only includes ratings when the obtained outcome was -50 or 50, and the unobtained outcome (missed or rejected) was -200 or 200. Error bars represent standard error. A figure with all combinations of obtained and unobtained outcomes is reported in the supplementary analyses (https://doi.org/10.17605/OSF.IO/N28BU).

consider two plausible explanations for the current results: (1) regret is dependent on counterfactual reasoning, but generation of the counterfactuals is not always demanding on reflective processes; or (2) the experience of regret is not always dependent on counterfactual reasoning.

The first possibility is that regret requires counterfactual reasoning but that counterfactual reasoning does not require reflective processing. Participants were genuinely simulating the hypothetical situation in which they made a different choice, but they achieved these counterfactual thoughts without the need for reflective processes. This suggestion is in line with the findings of Goldinger *et al.* (2003), who showed that judgements frequently associated with counterfactual reasoning are not diminished by concurrent working memory load and may even be amplified for individuals with low working memory capacity.

A more nuanced version of this explanation is that counterfactual thinking can be more or less complex, and that with increased complexity comes increased need for reflective processes. Simple counterfactual thoughts can be achieved without the need for reflective processes, whereas more complex counterfactual thoughts cannot. This corresponds to advances in the understanding of the development of counterfactual thinking. Research from Rafetseder and colleagues has demonstrated that young children are able to handle simple counterfactual statements, perhaps using heuristic strategies related to simple conditional reasoning (Rafetseder *et al.*, 2010; Rafetseder *et al.*, 2013; Rafetseder & Perner, 2014). However, reasoning with more complex counterfactual statements, that cannot be achieved using heuristic methods, does not emerge until later in childhood or adolescence. In line with this complexity account, Atkinson and colleagues (2009) found that when adults ascribe regret to others after reading brief vignettes, some features of counterfactual thinking but not others were impaired by responding under time pressure. In more complex situations, care must be taken to hold certain features of the past stable, while manipulating others – presumably relying on reflective processes. Thus, it may be that the gambling task, which involves visually displaying counterfactual outcomes, requires a relatively simple form of counterfactual reasoning.

The second explanation of our results is that the experience of regret is not always reliant on counterfactual thinking, at least as counterfactual thinking is usually conceptualized. In this line of argument, the question of whether counterfactual thinking is reliant on reflective processes is set aside because, regret can be experienced without the need for counterfactual thinking. According to this argument, regret can be achieved through lower-level processes. For example, when the situation allows, we may automatically monitor the outcomes of foregone choice alternatives, so these outcomes are available as a standard against which actual outcomes may be compared without the need to engage in effortful simulation of hypothetical past scenarios (c.f. Doan *et al.*, 2020). Evidence in favour of this monitoring comes from instances of counterfactual curiosity. Human adults (FitzGibbon *et al.*, 2021; Summerville, 2011), children (FitzGibbon *et al.*, 2019), and rhesus monkeys (Wang & Hayden, 2019) have all been shown to be motivated to gain information about foregone choice alternatives. Indeed, eye-tracking research with a similar task to the one employed in the current study showed that adults spend more time observing the rejected outcome than the missed outcome (Bault *et al.*, 2016). Such monitoring may make the relevant information available for counterfactual comparisons without the need for counterfactual reasoning.

The feasibility of the heuristic strategy of monitoring foregone decision options is likely related to the complexity of the decision space. In the lab, regret is typically measured after simple decisions between two options, so monitoring the rejected option is straightforward. The decisions we make in our everyday lives tend to be rather more complex, for example, we may choose an investment scheme from a vast array of alternatives, so monitoring the performance of all the alternatives is not feasible. These heuristic strategies may also be learned over time, through experience with decisions and their outcomes. We explored this possibility with supplementary analyses by testing for order effects between the working memory load conditions, on the assumption that experiencing the task with low working memory load may reduce cognitive costs over time and thus having the low load condition first may result in less impact of working memory load than having the high load condition first (see supplementary materials, https://doi.org/10.17605/OSF.IO/N28BU). This was not found to be the case. Nor was it the case that there was an effect of working memory load that was only present in the early experimental trials. Nonetheless, it may be that our participants had sufficient experience with these kinds of decisions that they were already able to use heuristic strategies from the start of the task.

Another related explanation for our findings is that the cognitively demanding simulation processes involved in counterfactual thinking can happen ahead of time at the point of making the decision rather than after the actual outcomes are known. If the participant has already generated the alternative possibilities prior to making the decision, and thus, in this design, prior to the loading of working memory, then the comparison of these possibilities may not require reflective thinking at all. This explanation could be tested in future research by loading working memory prior to presenting the gambles, so that the entire decision process happens under working memory load. If the experience of regret is still not disrupted by working memory load, then this would provide even stronger evidence that the kinds of cognitive processes required to generate counterfactual emotions put limited demands on central cognitive resources.

Although the evidence we present suggests that adults experience regret without the need for reflective processes, this is puzzling from a developmental perspective. The experience

of regret develops late relative to children's ability to handle simple counterfactual statements and monitoring of foregone choice alternatives. This late development suggests that there is more to experiencing regret than performing simple counterfactual thinking or monitoring rejected outcomes – both of which appear to develop early, at least in rudimentary form (FitzGibbon *et al.*, 2019; Nyhout & Ganea, 2019). The question remains whether there is a developmental shift from regret requiring high-level reflective processing in childhood to low-level heuristic processing in adulthood, and if so, what must develop for that shift to occur. For example, must new or more efficient cognitive processes be in place, or is greater experience with relevant decisions and their outcomes enough to support less cognitively demanding counterfactual emotions. Typically, when testing children's counterfactual thought and emotions, we use novel scenarios so that children cannot rely on basic conditional reasoning (Leahy *et al.*, 2014), but this may mean that children are forced to use more effortful processes in lab-based tasks than they or adults would typically use 'in the wild'. This could be explored in future research by manipulating the experience that children have with the kinds of decisions they are making and determining the effects of that prior experience on children's counterfactual emotions.

One concern is that our working memory manipulation did not disrupt reflective processing. While we cannot address this concern directly with our data, we point to two pieces of evidence that this is not the case. First, this manipulation has been previously shown to disrupt decision making in a delay discounting task, (Hinson *et al.*, 2003). Delay discounting also requires comparisons, but of hypothetical future scenarios (immediate small gain vs. delayed larger gain) rather than of past scenarios. Second, we have evidence that participants did engage with the working memory task and that the high load working memory condition was effortful for participants. Accuracy was very high overall, which suggests that participants did indeed hold the digits in mind. Participants were also less accurate and slower to respond to the memory prompt under high than low memory load, suggesting that this condition was demanding. Future research should address this limitation by employing a concurrent task that has greater working memory demands, for example an N-back task that has both working memory maintenance and updating demands.

In conclusion, we have demonstrated that the experience of regret in a gambling task is unaffected by concurrent working memory load. This suggests that in adults, regret is not always reliant on reflective cognitive processes. We have proposed two alternative explanations for these results: (1) that regret requires counterfactual thinking, but that counterfactual thinking does not require reflective processing; or (2) that regret does not (always) require counterfactual thinking. Open questions remain regarding whether the complexity of the decision space affects the need for recruitment of reflective processes, and whether there is a shift from high-level reflective processes in childhood, to low-level intuitive processes in adulthood.

Data availability

Open Science Framework: Experience of regret is unaffected by concurrent working memory load. https://doi.org/10.17605/OSF.IO/N28BU (FitzGibbon *et al.*, 2024).

Author contributions

Lily FitzGibbon: Conceptualization, Methodology, Software, Formal analysis, Visualisation, Writing - Original Draft; Writing - Review & Editing; Caroline Putt: Conceptualization, Methodology, Investigation, Formal analysis, Visualisation, Writing - Original Draft; Aidan Feeney: Writing - Review & Editing, Funding acquisition, Supervision; Teresa McCormack: Writing - Review & Editing, Funding acquisition, Supervision; Sarah Beck: Conceptualization, Methodology, Writing - Review & Editing, Funding acquisition, Supervision.

Acknowledgements

Glyn Humphreys (1954 – 2016) was a much-valued member of the original ESRC-funded project team that conducted this study.

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Publisher Full Text

Open Peer Review

Current Peer Review Status: ✔ ✔

Version 2

Reviewer Report 23 September 2024

https://doi.org/10.21956/routledgeopenres.19921.r28934

✔ **Shalini Gautam**
Department of Psychology, Boston College, Boston, England, UK

I'm happy to approve this updated version now, in light of the author's responses and edits. I feel they addressed my comments thoroughly and made clear and appropriate changes.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Counterfactual thinking, cognitive development

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 16 September 2024

https://doi.org/10.21956/routledgeopenres.19921.r28933

✔ **Claire Hales**
The University of British Columbia, Vancouver, British Columbia, Canada

I am satisfied that the authors have addressed reviewer comments, and have no further comments to make.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Behavioral (rodent) experiments, decision making, computational

neuroscience, psychiatric disorders including gambling, depression and addictions

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 20 May 2024

https://doi.org/10.21956/routledgeopenres.19287.r28231

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Shalini Gautam
Department of Psychology, Boston College, Boston, England, UK

This paper examines the interesting question of whether an experience of regret relies on a cognitive process that is fast and intuitive or slow and reflective. A working memory manipulation was utilized to explore whether participants' self-reported experiences of regret would be affected by a high memory load. If they were, this would indicate that regret is underpinned by a cognitively demanding reflective process. The authors used a gambling task where participants selected between two ‘chance wheels’ to win points. Disappointment was elicited when the participant’s chosen wheel yielded a poor outcome (by chance), and regret was elicited when the unchosen wheel yielded a better outcome than the participant’s chosen wheel. When viewing these outcomes and making subsequent emotion ratings, participants either held in mind a 5-digit number string (high memory load) or 2-digit number string (low working memory load). Results revealed no difference in participants' reported experiences of regret under either a high or low working memory load. The authors conclude this indicates that regret is not always a reflective process.

This paper was straightforward and well written, with a clear and innovative experimental approach. It also explores a topic that deserves more attention, and I enjoyed reading it. I do have a few questions that I think can be easily addressed. I wonder if there could be a bit more discussion of the key theory driving the research question. In the introduction the authors note that the reflective/intuitive dichotomy is not universally accepted, and I’m wondering if there could be some discussion of alternative theories that may align with the results. For example, the authors cite a paper (De Neys, 2021) that explains an alternative theory that the difference between intuitive/reflective processes is one of degree and not kind. Under this view, perhaps the reflection involved in experiencing regret is less cognitively demanding than other tasks implementing this manipulation (but still involves a degree of reflection). The authors also refer to the developmental literature as evidence that regret may rely on a reflective process initially, but perhaps become intuitive in adulthood. Is it possible that the reflection process itself becomes easier over time, especially in a simple task like this?

I'm curious that there seems to be no difference between the emotions in the disappointment outcomes and the regret outcomes. Was there a difference? If not, how did the authors distinguish if participants were feeling regret or disappointment? What does it mean for the interpretation of the results if these were not distinguished?

In the methods section, I'm wondering if some more clarity could be provided explaining how the task was run. Specific questions are: What did getting points mean to participants? Did participants sometimes win the trials (i.e., get the better outcome either in the partial or complete feedback conditions), and if so, how often did this happen?

The authors explain that the memory load was applied after participants chose a wheel. Is it possible that participants had already run through their hypothetical options at this point, and so when the load was applied and the outcome was revealed, they had already considered how they'd feel? This may have reduced the need for reflection when the outcome was revealed. Along these lines, if participants completed 120 trials, they may also have become quite acquainted to the task and understand all the outcomes without needing much reflection. Would it be worth looking at just the first few trials when participants may have needed to engage in reflection more?

Is the work clearly and accurately presented and does it engage with the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

Are all the source data and materials underlying the results available?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Counterfactual thinking, cognitive development

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 21 Aug 2024

Lily FitzGibbon

Thank you for your detailed and constructive feedback on our manuscript. We believe that the revised manuscript is now clearer from both a theoretical and methodological perspective. Below we have addressed each point in turn, repeating the reviewer comments in plain text *and providing our responses in itallics with indication of changes in the manuscript and additional supplementary analyses where appropriate.*

Reviewer Comment: In the introduction the authors note that the reflective/intuitive dichotomy is not universally accepted, and I'm wondering if there could be some discussion of alternative theories that may align with the results. For example, the authors cite a paper (De Neys, 2021) that explains an alternative theory that the difference between intuitive/reflective processes is one of degree and not kind. Under this view, perhaps the reflection involved in experiencing regret is less cognitively demanding than other tasks implementing this manipulation (but still involves a degree of reflection).

Response: *Thank you for pushing us to be more explicit about the theoretical underpinnings of the research. We agree that we should have been clearer that although dual systems theories are helpful for setting up our research question, our study design actually cannot differentiate between two qualitatively distinct systems and one system in which processes differ by degree. Indeed, as you point out, De Neys (2021) nicely illustrates that much of the evidence presented for dual systems can be just as well explained by a single system with a continuum of processes that are more or less reflective. What is important for our research is that cognitive processes can differ in the extent to which they draw on limited-capacity resources and can thus be characterised as more or less reflective.*

We are now explicit about our position and refer back this to when operationalising the research question. We have also moved the paragraph about dual systems accounts a little lower in the introduction to reduce the prominence of this account. To further strengthen the theoretical underpinnings, we also now include the theoretical perspective from Redshaw and Suddendorf (2020) later in the Introduction, who consider the representational resources required for different types of thought about possibility. These authors argue that regret requires working memory because it involves temporal embedding and simulation of alternative past events. Finally, we include an alternative developmental perspective from Buchsbaum and colleagues (2012) who suggest that children are already capable of counterfactual thought from around the age of three, as evidenced by their engagement in pretend play and causal learning.

Reviewer Comment: The authors also refer to the developmental literature as evidence that regret may rely on a reflective process initially, but perhaps become intuitive in adulthood. Is it possible that the reflection process itself becomes easier over time, especially in a simple task like this?

Response: *This is a great suggestion that would be fascinating to explore empirically. We have alluded to it in two places in the manuscript. First, when discussing the heuristic strategy account in the discussion, we suggest that these strategies may be learned over time through experience with decisions and their outcomes. We then come back to the idea when discussing developmental trajectories, posing the question of whether the developmental changes are*

related to new or more efficient cognitive processes, or to greater experience with decisions and their outcomes. We propose future research to test the effects of prior experience with decisions on children's counterfactual emotions.

Reviewer Comment: I'm curious that there seems to be no difference between the emotions in the disappointment outcomes and the regret outcomes. Was there a difference? If not, how did the authors distinguish if participants were feeling regret or disappointment? What does it mean for the interpretation of the results if these were not distinguished?

Response: *This is an important issue, and one that is a little challenging to address within the current dataset. In our analysis, we used Bayesian hypothesis testing to test the amplification effect (the effect that outcomes missed by choice are experienced more keenly than those missed by change). This is frequently conceptualised as regret vs. disappointment. We demonstrated that the outcome rejected by choice (the outcome of the other wheel) had a greater influence on emotion ratings than the outcome missed by chance (the other outcome on the chosen wheel) within 'complete' trials, where both outcomes were available to participants.*

However, observing the parameter estimates across the models of complete and partial trials, it is clear that the effect of missed outcome on partial trials (b = -0.40 [-0.52, -0.29]) was comparable to the effect of rejected outcomes on complete trials (b = -0.43 [-0.59, -0.26]). Bayesian hypothesis testing across different models is not advised, so the evidence for a difference in these effects cannot easily be determined but based on the overlap in confidence intervals, these responses are not strongly distinguished. In previous work using the same paradigm (e.g., Bault et al., 2016; Camille et al., 2009), direct comparisons were made across partial and complete trials while controlling for obtained outcomes by only considering the 'relevant' unobtained outcomes (the missed outcome on the chosen wheel for partial trials and the outcome of the rejected wheel for complete trials).

In line with these previous studies, applying the same treatment here does produce an interaction between the unobtained outcome and trial type, such that the effect of the unobtained outcome has a greater effect on emotion ratings on complete than partial trials (b = -0.17 [-0.28, -0.06], p = .002). However, including both in the same model does not account for the variance explained by the missed outcome on complete trials which may bias this comparison. One might question whether demonstration of the amplification effect is a necessary condition a difference in processing between disappointment and regret – it is possible to imagine that different processes could lead to comparable emotional responses. Indeed, previous fMRI and eye-tracking research using the same paradigm has indeed evidenced different processing of these types of trials (Bault et al., 2016; Coricelli et al., 2005).

Thus, we are reluctant to make claims about the lack of distinction between regret and disappointment based on the similarity in emotional responses between partial and complete trials. The additional analysis is now reported in the Supplementary Materials and referred to in the manuscript after presentation of the original test of the amplification effect.

Reviewer Comment: In the methods section, I'm wondering if some more clarity could be provided explaining how the task was run. Specific questions are: What did getting points

mean to participants?

Response: *There were no extrinsic rewards in the task, participants were not rewarded for getting more points. Participants also did not receive feedback about the accumulation of points across the task. Responses to the experience of winning or losing points are assumed to be based on participants' intrinsic motivation. This is now stated more clearly in the Method section, both in the Participants section and in the Procedure.*

Reviewer Comment: Did participants sometimes win the trials (i.e., get the better outcome either in the partial or complete feedback conditions), and if so, how often did this happen?

Response: *All combinations of obtained and unobtained outcomes were possible, with the exception that the obtained and unobtained outcomes were the same. Participants received a rewarding outcome (50 or 200 points) on 62% of trials. Participants obtained the a better outcome than the rejected and/or missed outcomes (i.e., they 'won' the trial) on 51% of trials. The average proportion of trials receiving each outcome and the proportion of 'winning' trials is now reported in the Procedure.*

Reviewer Comment: The authors explain that the memory load was applied after participants chose a wheel. Is it possible that participants had already run through their hypothetical options at this point, and so when the load was applied and the outcome was revealed, they had already considered how they'd feel? This may have reduced the need for reflection when the outcome was revealed.

Response: *This is an interesting idea that we had previously neglected to include in the final manuscript. We have now included this as another alternative explanation with a suggested design for a future study to test this explanation in the Discussion.*

Reviewer Comment: Along these lines, if participants completed 120 trials, they may also have become quite acquainted to the task and understand all the outcomes without needing much reflection. Would it be worth looking at just the first few trials when participants may have needed to engage in reflection more?

Response: *We have now addressed this in two ways, both now presented in the supplementary materials. First, since the trials were delivered in a blocked design, we included the effect of block order as an additional interaction term in the models. Order did not interact with any of the main effects of outcome, nor with the interactions between load and each outcome in either model. This suggests that having done a full block of low-load trials did not modify the effect of the working memory load condition. Second, as suggested, we repeated the analysis with the first ten trials from each block and again found no interactions with working memory load. These analyses are now included in the Supplementary Materials and referred to in the Discussion when discussing the role of prior experience.*

Competing Interests: No competing interests were disclosed.

Reviewer Report 22 March 2024

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In this study the authors use a straightforward behavioral task design to probe whether the cognitive processes underlying the feeling of regret are fast, intuitive processes or slower, reflective processes. The task design combined two elements – a working memory manipulation alongside a regret-inducing gambling task. Whilst observing the outcome of a chosen, and/or rejected gambling wheel, participants had to hold in mind a number string and keep this in memory whilst making and emotional rating following wins and losses. They found that concurrent working memory load did not impact participants reporting of regret, suggesting that, at least for this simple laboratory task, regret is not reliant on reflective cognitive processes. The authors include a comprehensive discussion about the impact of this work, encompassing multiple possible different explanations for how regret might manifest differently across ages and contexts. Importantly, this work was also able to reproduce previous findings in the literature. It is a well written article that is methodologically sound, with appropriate statistical analysis and interpretation of results. I only have one minor suggestion for improvement. The authors state in the figure legend that “For ease of comparison with previous research (e.g., Camille et al., 2004; Coricelli et al., 2005), the figure only includes ratings when the obtained outcome was -50 or 50, and the unobtained outcome (missed or rejected) was -200 or 200.” Could the authors also include the rest of the comparisons in another figure? This would increase transparency and may be of interest to other readers.

Is the work clearly and accurately presented and does it engage with the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

Are all the source data and materials underlying the results available?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Behavioral (rodent) experiments, decision making, computational neuroscience, psychiatric disorders including gambling, depression and addictions

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 21 Aug 2024

Lily FitzGibbon

Thank you for taking the time to review our work and for the thorough assessment of the manuscript. We agree that a figure showing all outcome combinations increases the transparency of the reporting, however the complexity of the figure makes it somewhat challenging to interpret.

We have included this figure in the supplementary materials and refer the reader to it at the end of the caption for the original figure. In response to a comment from Reviewer 2, we also now include the mean number of trials in which each outcome was obtained to further increase the transparency of the reporting within the manuscript.

Competing Interests: No competing interests were disclosed.