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Mapping the Dose–Response Relationship Between Monetary Reward and Cognitive Performance

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The relationship between reward value and cognitive performance is often thought to be curvilinear, shaped like an inverted U. Moderately valuable rewards should facilitate, but extremely valuable rewards should harm, performance. Despite the popularity of this idea, the dose–response relationship between reward value and cognitive performance is not yet well understood. Here, we present a set of experiments (total $N = 254$) that examine the effects of monetary reward (no reward, medium reward, extreme reward) on task-switching performance. Overall, more valuable rewards led to better performance. Yet, when physical reward cues were present (i.e., when the money at stake was placed on the table), we observed the predicted inverted U-shaped relationship. Together, our results suggest that (a) people are often able to maintain good cognitive performance when the stakes are high and that (b) physical reward cues may play a key role in triggering "choking under pressure."

Keywords: incentives, Yerkes–Dodson law, metacontrol, cognitive flexibility, value-driven attentional capture

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Monetary rewards boost human performance on a wide variety of tasks across a wide variety of conditions (Frömer et al., 2021; Garbers & Konradt, 2014; Liljeholm & O'Doherty, 2012; Zedelius et al., 2014). At the same time, monetary rewards also have well-documented undesirable effects. One of these effects is *choking under pressure*, that is, performance impairments that occur when the stakes are very high (Beilock et al., 2004; Mobbs et al., 2009). So, rewards can both boost and impair human performance. A common explanation for this paradoxical pattern is that the dose–response relationship between reward value and performance is nonlinear. Specifically, both in science and in practice (Ariely et al., 2009; Pink, 2011), moderately valuable rewards are often thought to facilitate performance; extremely valuable rewards are often thought to interfere with performance.

The latter idea stems from a combination of two classic assumptions. First, often referred to as the "Yerkes–Dodson law,"[1] the link between arousal and performance is commonly assumed to follow the shape of an inverted U (e.g., Aston-Jones & Cohen, 2005). Second, arousal is commonly assumed to respond to the value of anticipated rewards (at least when rewards can be earned through performance on challenging-but-not-impossible tasks; see Bijleveld et al., 2009; Bouret & Richmond, 2015; Duffy, 1957; Mobbs et al., 2009). Combining these two ideas, performance should be highest when moderately valuable (vs. less valuable and extremely valuable) rewards are at stake (Ford et al., 1985).

In this research, we examine the shape of the dose–response relationship between reward value and human performance. We focus on cognitive performance, and we contribute to the literature in three ways:

First, despite that the Yerkes–Dodson law is often used as a post hoc explanation for various reward-related phenomena (Corbett, 2015; Teigen, 1994), there is little direct empirical evidence for its validity. That is, most studies on the link between reward and cognitive performance have used only two levels of reward (e.g., low and high; Chiew & Braver, 2014; Fröber & Dreisbach, 2016; Rusz et al., 2018), and thus cannot detect nonlinear relationships. The studies that did use three (or more) levels of reward on performance either focused only on motor performance (Chib et al., 2012, 2014; Dunne et al., 2019; Lee & Grafton, 2015) or suffered from methodological limitations (e.g., between-subjects design with small cell sizes; Ariely et al., 2009). Thus, the field needs studies that test

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[1] A historical note: Yerkes and Dodson (1908) showed that mice learned their way through a maze fastest when medium-intensity shocks (as compared to low-intensity and high-intensity shocks) were used as punishments. Sample sizes were small, and conclusions were based solely on descriptive statistics. Nevertheless, this paper has been reinterpreted and overgeneralized in many ways over the years, which gave rise to the phrase "Yerkes–Dodson law." However, the "law" has little to do with the original experiments. For critical reviews, see Corbett (2015), Teigen (1994), and Winton (1987).

the effect of at least three levels of reward—that is, no reward, medium reward, and extreme reward—on cognitive performance, preferably within-subjects. Here we report a set of such studies.

Second, we explore two candidate cognitive mechanisms through which (extremely valuable) rewards may disrupt performance. We draw from metacontrol models (Dreisbach & Fröber, 2019; Eppinger et al., 2021; Fröber & Dreisbach, 2021; Hommel, 2015), which suggest that cognitive control stems from the interplay of two antagonistic systems. The first of these systems supports *persistence*, that is, people's ability to maintain goals over time and shield these goals from distractions. The second supports *flexibility*, that is, people's ability to adjust goals in response to changes in the environment. According to metacontrol models, (healthy) people balance these systems depending on situational requirements. That is, in some situations, it pays off to be relatively persistent (e.g., when trying to finish a work task before lunch); in other situations, it pays off to be relatively flexible (e.g., when trying to take care of a toddler; Hommel, 2015). As the balance between these systems is underpinned by the dopamine pathways, dopamine-related psychiatric disorders are often accompanied by either overly persistent or overly flexible behavior (Cools et al., 2019).

We suggest that extreme rewards can impair cognitive performance in either of two ways. On the one hand, it could be the case that extreme rewards shift the balance toward persistence, but to such an extent it makes people overly focused on the task at hand. Such an overfocused state can, at least on some tasks, impair performance (Beilock & Carr, 2001; Bijleveld et al., 2011a; Glucksberg, 1962; Markman et al., 2006). On the other hand, it could be the case that extreme rewards shift the balance toward flexibility (Fröber & Dreisbach, 2021), but to such an extent that people can no longer successfully focus on the task at hand and become distractible. This possibility would be in line with the prior finding that people, in high-stakes situations, often experience task-irrelevant thoughts (e.g., "What if I fail? I really need to perform well now!"), which are linked to impaired performance (Beilock et al., 2004; Ramirez & Beilock, 2011).

To examine how extreme rewards may impair performance, we use a rewarded task-switching task (van de Groep et al., 2017), in which people have to switch back and forth following two sets of instructions (i.e., to indicate whether a letter is a vowel or a consonant vs. to indicate whether a digit is odd or even). Trials in which instructions are different from the previous trial are called *switch trials*; trials in which instructions are the same as the previous trial are called *repeat trials*. If extreme rewards make people overly persistent, they should impair performance on switch trials. Conversely, if extreme rewards make people overly flexible, they should impair performance on repeat trials.

Third, we propose that the presence of reward cues (i.e., stimuli that signal that rewards are at stake) should affect how rewards impact cognitive performance. This proposal is based on research that suggests that reward cues—when encountered during task performance—can disrupt ongoing mental processes and, thus, harm performance. In one experiment (Zedelius et al., 2011, Experiment 2), for example, participants carried out a working memory task. During the maintenance of the to-be-recalled items, participants were exposed to a reward cue. Findings indicated that high-value (vs. low-value) reward cues impaired, rather than improved, performance. In another experiment (Anderson, 2016), participants completed a visual search task. In some trials of this task, participants were exposed to a sound that was previously associated with a monetary reward. On such trials, participants were slower, rather than faster, to successfully complete the visual search trial. These studies, along with others (for a meta-analysis, see Rusz et al., 2020), suggest that reward cues, (a) when they indicate that a high-value reward is at stake and (b) when they appear during task performance, can interfere with the cognitive processes that support performance. In other words, the presence of physical reward cues—for example, coins and banknotes that can be earned—may increase the likelihood that (extremely valuable) rewards impair cognitive performance. Here we test this possibility.

Experiments 1a and 1b provide a first examination of the dose–response relationship between reward value and task-switching performance. Experiment 1a uses a gain frame and Experiment 1b a loss frame (as gains vs. losses may trigger different speed–accuracy trade-offs; Leng et al., 2021), but are otherwise identical. Experiment 2 examines whether the presence of physical reward cues changes the shape of the relationship between reward value and cognitive performance. Finally, we provide a pooled analysis of all experiments that are reported in this article.

Experiments 1a and 1b

Method

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We preregistered our hypotheses and analysis plans (Experiment 1a: https://aspredicted.org/ya8tw.pdf; Experiment 1b: https://aspredicted.org/tw6ky.pdf). Materials, data, and analysis scripts are available at https://osf.io/5368s/.

Participants and Design

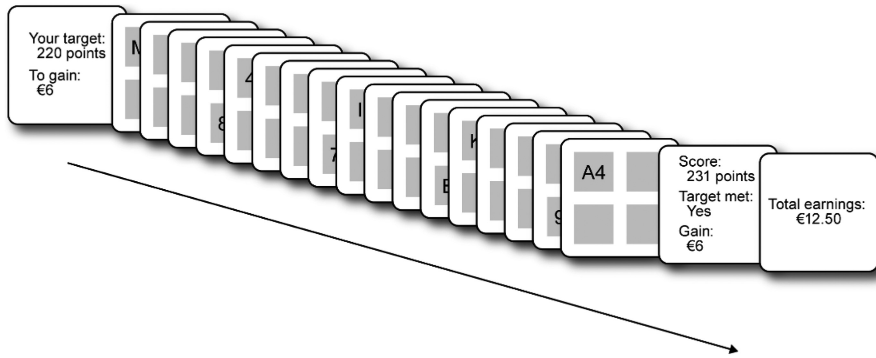
To determine sample size, we carried out a simulation-based power analysis (based on two preliminary experiments, which are reported in the online supplemental materials; see Green & MacLeod, 2016), which suggested that we could detect $\geq$50 ms increases in reaction times (RTs; for extreme reward vs. medium reward, within-subjects) with $\geq$90% power with 35 participants per study. Effects of at least this magnitude are plausible based on prior work on choking under pressure (van de Groep et al., 2017). To account for potential equipment failure and no-shows, we scheduled 40 participants per study. Thirty-nine participants (28 female; mean age = 21.9) took part in Experiment 1a; 37 participants (28 female; mean age = 22.0) in Experiment 1b. Participants were recruited from the university community.

Both studies had a within-subjects design. All participants carried out an incentivized task-switching task (adapted from van de Groep et al., 2017), which consisted of three no-reward blocks, three medium-reward blocks, and three extreme-reward blocks. In Experiment 1a, rewards were presented as potential gains; in Experiment 1b, as potential losses. The experiments were otherwise identical. All experiments were approved by the local ethics committee.

Task

Participants completed 18 blocks (nine practice blocks, nine experimental blocks; see below) of 17 trials each. On each trial of the task, a letter and a digit appeared in one quadrant of the screen (Figure 1). In the first trial of each block, these stimuli appeared in

Figure 1
Schematic Representation of One Block



Note. In each block, participants first learned their point target and the magnitude of the reward. Then, they completed 17 trials. Finally, participants received feedback on their score and their reward.

the top–left quadrant; in the remaining 16 trials, the stimuli appeared clockwise in the next quadrant. If the stimuli appeared in either of the top quadrants, participants had to do the *letter task*, that is, they had to indicate whether the letter was a vowel or a consonant. If the stimuli appeared in either of the bottom quadrants, participants had to do the *digit task*, that is, they had to indicate whether the digit was odd or even. Thus, the task consisted of *repeat trials* on which participants did the same task as on the previous trial and *switch trials* on which participants did the other task.

Participants responded by pressing "Z" (vowel or odd) or "M" (consonant or even) on the keyboard. Letters and digits were drawn randomly from predetermined sets (GKMRAEIU and 23456789). This draw was done with replacement, but with the restriction that letters and digits were never the same as those that were presented on the preceding trial. Each response by participants was followed a 150 ms blank screen. After that, the next trial started immediately.

Procedure

After giving informed consent, participants were seated in cubicles. Participants first familiarized themselves with the task by completing nine practice blocks. After each practice block, participants received feedback on their performance. After practice blocks 1–3, participants received feedback on the total time in which they completed the block (in seconds) and on their accuracy (in number of errors). Before starting practice block 4, participants learned that, from then on, their speed and accuracy would be converted into *points*. Accordingly, after each of the remaining practice blocks (4–9), participants received feedback only on the number of points they scored.

Points were computed after each block, as follows. We first computed a base score $A = 500 -$ (total response time in milliseconds/100). Next, we computed an error penalty $B = 2 \times$ (number of mistakes).[2] The error penalty reflected the percentage of the base score that participants would lose due to their errors. As such, we computed a final score $S = A \times ([100 - B]/100)$ with $S \leq 0$. Put simply, participants received a higher score when they were faster and/or made fewer errors.

After the practice blocks, participants carried out nine experimental blocks. In the experimental blocks, participants could earn money (Experiment 1a) or avoid losing money (Experiment 1b) by being fast and accurate. Specifically, before each block, participants saw a target score (in points) and the monetary reward that was at stake (Figure 1). Blocks varied in the value of the reward that was at stake—that is, participants could earn either *no reward* (€0.00), a *medium reward* (€0.50), or an *extreme reward* (€10.00) by being fast and accurate during that block. Each reward level occurred three times, in random order. Between blocks, there were brief breaks (5 s).

On average, participants needed 17 s ($SD = 3$) to complete one block. A rate of €10 per 17 s of work translates to $\pm$€2,100 per hour. For comparison, the minimum wage in the Netherlands is currently about €10 per hour. Therefore, we felt that a €10-per-block reward could reasonably be described as "extreme" in the context of our task.

Experiment 1a used a *gain frame*. Participants started out with €0. By attaining or exceeding the target score of a block, they earned the amount of money that was at stake at that block. Experiment 1b used a *loss frame*. Participants started out with €31.50. By attaining or exceeding the target score, they avoided losing the monetary reward at stake. As such, in both experiments, participants could earn (or keep) anywhere between €0 and €31.50.

To ensure that the task was challenging for all participants, point targets were set individually, based on performance during the practice blocks. Specifically, the target was the highest score from the nine practice blocks, with uniform noise (range: -10 to $+10$ points). The noise was added to make sure that targets would not be exactly the same each block. On average, participants met or exceeded the target score on 43% of the blocks in Experiment 1a and on 49% of the blocks in Experiment 1b.

Analyses

To preserve the nested structure of our data (trials within participants), we used mixed-level linear models, in which the trial was the level of analysis. We analyzed response times and accuracy separately. For both RTs and accuracy, we started out with a model that included the fixed main effect of trial type (repeat vs. switch) and the fixed main effect of reward value (no reward, medium reward, and extreme reward), to test our primary hypothesis. We examined the predicted inverted U shape with by examining two comparisons: (a) no reward versus medium reward and (b) medium reward versus extreme reward.[2]

Then, a secondary analysis, we ran a model that included the trial type × reward interaction, in addition to the main effects, to examine whether rewards had different effects on repeat versus switch trials. As for the random effects, we used a maximal model—that is, a model that includes a random intercept and random slopes for all within-subjects predictors (Barr et al., 2013). We chose this random-effects structure to take into account that some people may generally perform better than others and that some people respond more strongly to reward than others.

All models were implemented using the *lme4* package for R (Bates et al., 2014). Before analyzing RTs, we excluded RTs from trials on which participants were not accurate and RTs that fell outside 3 *SD* of the participant's mean (1.6% of trials in Experiment 1a; 1.5% in Experiment 1b). To compute p-values, we estimated degrees of freedom using Satterthwaite's method (Kuznetsova et al., 2017).

We further explored how reward value affected *switch costs* (operationalized as the RT difference between switch and repeat trials). As we had no hypotheses about switch costs, these analyses appear in the online supplemental materials.

Results

Experiment 1a

RTs. Data from Experiment 1a are summarized in Figure 2a. There was a significant main effect of reward on RTs, $\chi^2(2) = 14.00$, $p < .001$. Specifically, there was no significant difference in RTs between no-reward blocks and medium-reward blocks, $b = -11$, $SE = 13$, $t(37.4) = -0.84$, $p = .409$; however, participants were faster in extreme-reward blocks compared to medium-reward blocks, $b = -40$, $SE = 15$, $t(37.7) = -2.58$, $p = .014$. Furthermore, there was a main effect of trial type, $b = -147$, $SE = 12$, $t(37.8) = -12.47$, $p < .001$, which indicated that participants were faster on repeat trials than on switch trials. The reward × trial type interaction was not significant, $\chi^2(2) = 4.93$, $p = .085$, indicating that there was no evidence that the effect of reward was stronger on either of the trial types.

Accuracy. Participants were highly accurate under all conditions ($M = .95$). The main effect of reward was not significant, $\chi^2(2) = 0.20$, $p = .905$, suggesting that there was no evidence that accuracy depended on the amount of money that could be earned on that block. The main effect of trial type was significant, $b = 0.5$, $SE = 0.1$, $z = 5.35$, $p < .001$, indicating that participants were more accurate on repeat trials ($M = .97$) than on switch trials ($M = .93$). The reward × trial type interaction was not significant, $\chi^2(2) = 0.94$, $p = .625$.

Experiment 1b

RTs. Data from Experiment 1b are summarized in Figure 2b. We found a significant main effect of reward, $\chi^2(2) = 14.20$, $p < .001$. Specifically, participants were significantly faster in medium-reward blocks compared to no-reward blocks, $b = -54$, $SE = 19$, $t(34.2) = -2.86$, $p = .007$. However, there was no significant difference in RTs between medium-reward blocks and extreme-reward blocks, $b = -15$, $SE = 19$, $t(32.8) = -0.78$, $p = .440$. Furthermore, there was a significant main effect of trial type, $b = -179$, $SE = 15$, $t(36.0) = -12.14$, $p < .001$, which indicated that participants were faster on repeat trials than on switch trials. The reward × trial type interaction was not significant, $\chi^2(2) = 1.79$, $p = .408$, suggesting that there was no evidence that the effect of reward was stronger on either of the trial types.

Accuracy. Participants were very accurate under all conditions ($M = .95$). The main effect of reward was significant, $\chi^2(2) = 8.66$, $p = .013$. Specifically, participants were slightly more accurate in medium-reward blocks ($M = .95$) and extreme-reward blocks ($M = .95$) compared to no-reward blocks ($M = .94$). The main effect of trial type was significant, $b = -0.5$, $SE = 0.1$, $z = 5.32$, $p < .001$, again indicating that participants were more accurate on repeat trials ($M = .97$) than on switch trials ($M = .93$). The reward × trial type interaction was not significant, $\chi^2(2) = 1.61$, $p = .447$.

Discussion

We found no evidence for an inverted U-shaped relationship between reward value and performance, neither in a gain frame (Experiment 1a) nor in a loss frame (Experiment 1b). Rather, more valuable rewards increased performance. For gains, the increase in performance was clearest between no reward and a medium reward; for losses, the increase in performance was clearest between medium reward versus extreme reward. This pattern may be explained post hoc by loss aversion: Losses have a greater subjective impact than gains (Kahneman & Tversky, 1984); so, for losses, performance effects may manifest at comparatively lower values. We found no evidence that the relationship between reward value and performance had a different shape for repeat trials versus switch trials.

These results surprised us, as they contradicted previous research on choking under pressure (Ariely et al., 2009; Beilock et al., 2004; Mobbs et al., 2009). Participants were able to perform well despite that extremely valuable rewards were at stake. In fact, under extreme rewards, participants' performance was highest.

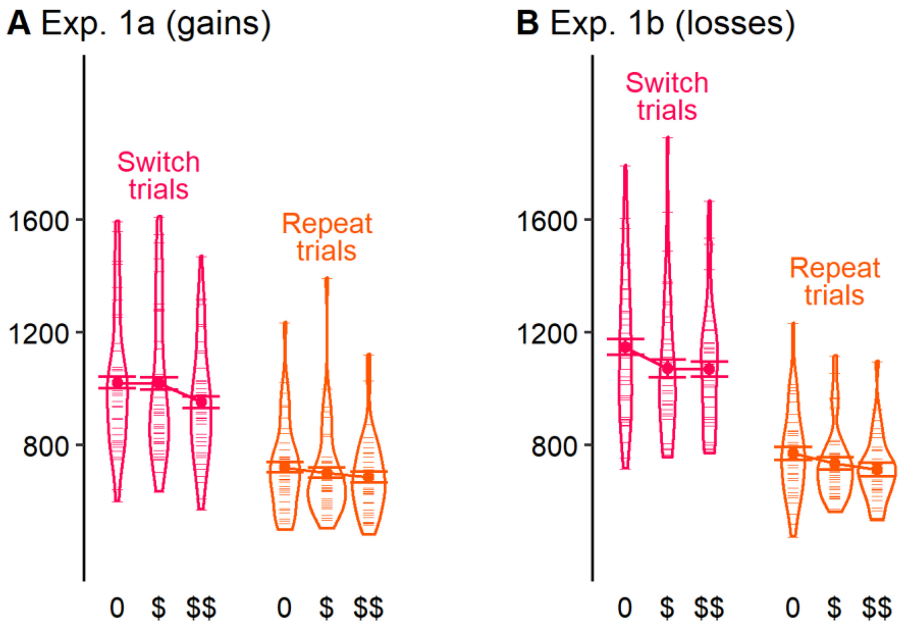
Experiment 2

Why did participants perform so well despite the presence of extreme rewards? A potential explanation lies in the fact that, in Experiment 1, participants worked in a sterile, distraction-free environment.

Two lines of research suggest that the presence of physical stimuli that remind people of the extreme rewards at stake may be a crucial trigger of performance impairments. First, in prior research on choking under pressure, researchers typically used a standardized protocol to induce high motivation (Beilock et al., 2004; Boere et al., 2016; Ramirez & Beilock, 2011). Under this protocol, participants are usually confronted with several cues that remind them that they urgently need to maximize their performance (e.g., a video camera close to the participant; an experimenter delivering scripted reward instructions throughout the session). It seems plausible that

[2] An alternative approach to probing the hypothesized inverted-U would be to test the contrast [1 × medium reward − ½ × no reward − ½ × extreme reward]. A disadvantage of using this contrast would be that it may turn out to be significant even in the absence of a clear drop in performance from medium to extreme reward. As examining this drop in performance was one of our key aims, we chose to test our predictions by separately testing the no reward versus medium reward and the medium reward versus extreme reward contrasts.

Figure 2
Reaction Times (ms) as a Function of Reward and Trial Type



Note. Error bars indicate within-subjects confidence intervals (Cousineau, 2005). Light horizontal bars indicate individual subjects' means. 0 = no reward; $ = medium reward; $$ = extreme reward. (A) Data from Experiment 1a. (B) Data from Experiment 1b. See the online article for the color version of this figure.

these visual aspects of the protocol increase the likelihood of performance impairments. Second, research on *value-driven attention* shows that task-irrelevant stimuli that were previously associated with valuable rewards are more likely to capture attention and more likely to disrupt the primary task (Anderson et al., 2011). A meta-analysis of this phenomenon suggests that value-driven attention affects performance on a range of tasks, including cognitive control tasks (Rusz et al., 2020; for example, see Krebs et al., 2010).

Experiment 2 was similar to Experiment 1b, with the key difference that Experiment 2 introduced a condition in which participants were exposed to reward cues—that is, to the money that was at stake. In this condition, the coins and banknotes that could be earned were placed on the desk, in view of the participant. We predicted that the drop in performance (from medium to extreme rewards) should be most pronounced when money is on the table.

Method

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We preregistered our hypotheses and analysis plans on aspredicted.org (https://aspredicted.org/vv6w7.pdf). Materials, data, and analysis scripts are available at https://osf.io/5368s/.

Participants and Design

We recruited 80 people (60 female; mean age = 21.6) from the university community to participate in Experiment 2. Participants were randomly assigned to either of the physical-presence-of-money conditions, with the restriction that the distribution of males and females was kept approximately constant between conditions (money on display, $n = 42$, of which 31 female; control, $n = 38$, of which 29 female). As before, and as preregistered, we excluded trials of which the RT fell outside 3SDs of the participant mean (1.7% of trials).

Experiment 2 was powered to detect drops in performance within-subjects (from medium to extreme reward), separately for both between-subjects conditions. As such, we reused the results from the power simulation we did for Experiments 1a and 1b, which suggested that we would need 35 participants per condition to detect $\geq$50 ms increases in RT with 90% power. We aimed for 80 participants in total to consider the possibility of equipment failure and no-shows.

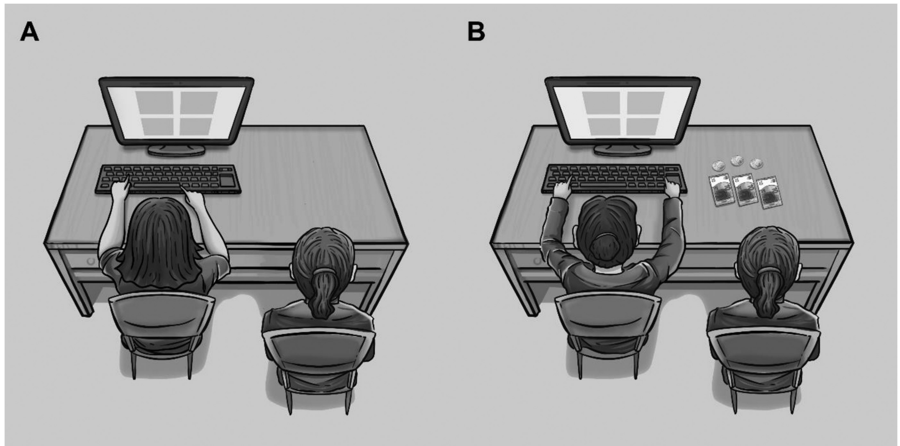
Procedure

Experiment 2 started out in the same way as Experiment 1b. That is, participants were welcomed to the lab, seated in a cubicle, and got familiar with the task by completing nine practice blocks. However, unlike in Experiment 1b, participants were now told to call the experimenter after they had finished the practice blocks. When they did so, the experimenter entered the cubicle.

In the control condition, the experimenter explained to participants that they would start off with €31.50—but that they could lose that money during the experiment. Then, the experimenter sat down next to, and slightly behind, the participant; next, the task began. The experimenter did not do or say anything until the task was finished. At that point, the experimenter paid the participants the money that they did not lose.

In the money-on-display condition, the experimenter placed three €10 bills and three 50c coins on the table, in view of the participant (Figure 3). The experimenter then explained that the money on the

Figure 3
Schematic Illustration of the Setup of Experiment 2



(A) Control condition. (B) Money-on-display condition.

table was theirs to take home—but that they could lose that money during the experiment. Then, the experimenter sat down in the same spot as in the control condition; next, the task began. Whenever participants failed to meet a target during a reward block, the experimenter removed the corresponding amount of money (i.e., one of the €10 bills or one of the 50c coins) from the table. Other than that, the experimenter did not do or say anything until the task was finished. The experimenter took care to remove money only after the blocks (i.e., when the feedback screen was visible; never during task performance). After the experiment, participants were paid the money that was still on the table.

In sum, in both conditions, the experimenter was present in the same cubicle as the participant. The crucial difference was that, in the money-on-display condition, the to-be-earned money was laid out on the table and was being taken away when participants failed to meet their targets on reward blocks. On average, participants met or exceeded their target on 47% of the blocks.

Analyses

We used the same analytic strategy as in Experiments 1a–b. We fitted a mixed-level linear model with just the main effect of reward, to examine the hypothesized inverted U across conditions. Then, we added the main effect of the physical presence of money and the physical presence of money × reward interaction. As a secondary analysis, we examined whether the physical presence of money × reward interaction was different for repeat trials versus switch trials. All models were maximal models, that is, models that include a random intercept and random slopes for all within-subjects predictors (Barr et al., 2013).

Results

RTs

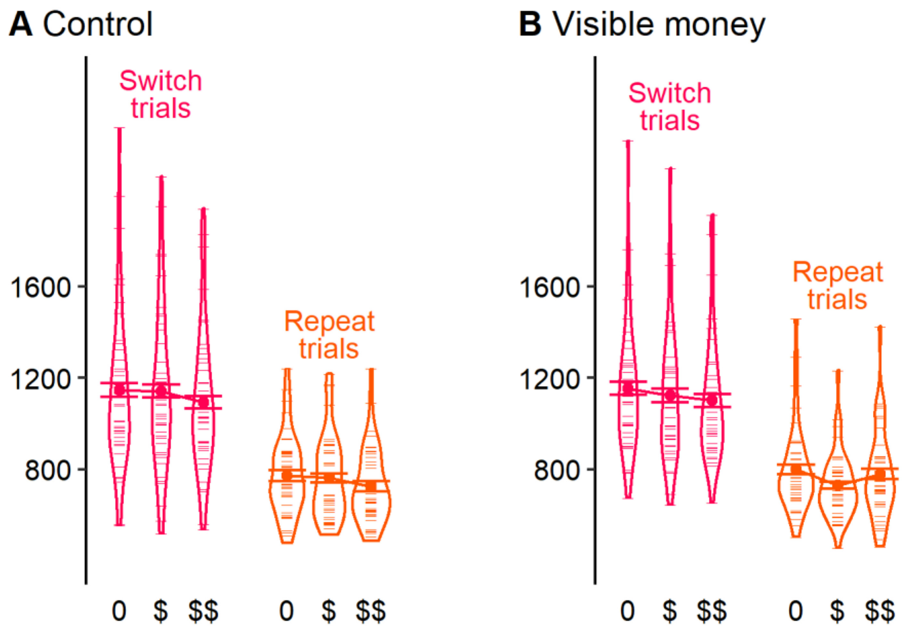
Data from Experiment 2 are summarized in Figure 4. We first estimated the reward–performance relationship across both conditions, using the same analysis we used for Experiment 1—that is, without taking into account whether the money was on display. In this analysis, the main effect of reward was significant, $\chi^2(2) = 13.49$, $p = .001$. Participants were significantly faster in medium-reward blocks compared to no-reward blocks, $b = -29$, $SE = 12$, $t(78.1) = -2.54$, $p = .013$. However, there was no significant difference in RTs between medium-reward and extreme-reward blocks, $b = -15$, $SE = 12$, $t(76.0) = -1.25$, $p = .216$. The main effect of trial type was significant, $b = -182$, $SE = 11$, $t(78.6) = -16.87$, $p < .001$, indicating that participants were faster on repeat trials than on switch trials.

We next tested the prediction that the reward–performance relationship depends on the physical presence of reward cues. To this end, we added the reward × physical presence of money interaction to the model, which was significant, $\chi^2(2) = 6.76$, $p = .034$. Specifically, the physical presence of money did not significantly affect the difference between no-reward blocks and medium-reward blocks, $b = 21$, $SE = 11$, $t(77.3) = 1.91$, $p = .060$. However, the physical presence of money did affect the RT difference between medium-reward and extreme-reward blocks, $b = -27$, $SE = 11$, $t(75.7) = -2.40$, $p = .019$. To further interpret this interaction, we inspected the pattern of means (Figure 4). This inspection suggested that the pattern of results was different for switch versus repeat trials. Thus, we proceeded by testing the effects of reward and physical presence separately for switch trials versus repeat trials[3]:

Among switch trials, there was a main effect of reward, $\chi^2(2) = 9.21$, $p = 0.010$, showing that participants were faster when more money was at stake (Figure 4, pink lines), but this effect was not

[3] An alternative way to test whether the effects of reward value were different for repeat trials and switch trials is to examine the reward × trial type interaction within each of the physical presence of money conditions. As our preregistration was not specific on this issue (i.e., we planned to examine if the predicted U shape would be more pronounced on either of the two trial types), we also tried this alternative strategy. To summarize, we found that trial type interacted with reward (medium vs. extreme) in the money-on-display condition, $b = 35$, $SE = 16$, $t(52.4) = 2.20$, $p = .032$, but not in the control condition, $b = 5$, $SE = 13$, $t(139.5) = 0.36$, $p = .719$.

Figure 4
Reaction Times (ms) as a Function of Reward and Trial Type



Note. Error bars indicate within-subjects confidence intervals (Cousineau, 2005). Light horizontal bars indicate individual subjects' means. 0 = no reward; \$ = medium reward; \$\$ = extreme reward. (A) Control condition. (B) Money-on-display condition. See the online article for the color version of this figure.

moderated by the physical presence of money, $\chi^2(2) = 0.69$, $p =$ 0.708.

Among repeat trials, the main effect of reward, $\chi^2(2) = 10.97$, $p = .004$, was qualified by the reward × physical presence of money interaction, $\chi^2(2) = 15.13$, $p < .001$. Specifically, when money was *not* physically visible (Figure 4, left panel, orange line), there was no evidence for a RT difference between medium-reward blocks versus no-reward blocks, $b = -12$, $SE = 18$, $t(40.3) = -0.64$, $p = .524$; and participants were somewhat faster in extreme-reward blocks versus medium-reward blocks, $b = -37$, $SE = 17$, $t(40.2) =$ -2.16, $p = .037$. Thus, if anything, when money was not on the table, on repeat trials, people become faster when more money was at stake. However, when money was physically visible, mean RTs for repeat trials showed a U-shaped pattern (Figure 4, right panel, orange line). That is, participants were faster in medium-reward versus no-reward blocks, $b = -71$, $SE = 18$, $t(68.4) = -3.97$, $p < .001$; yet, participants were slower in extreme-reward versus medium-reward blocks, $b = 49$, $SE = 18$, $t(59.7) = 2.68$, $p = .010$.

Accuracy

As in Experiment 1, participants were highly accurate under all conditions ($M = .95$). As we did for RTs, we first estimated the incentive–performance relationship across both treatments, akin to the analysis that we used for Experiment 1. In this analysis, the main effect of reward was not significant, $\chi^2(2) = 1.39$, $p = .499$. The main effect of trial type was significant, $b = -0.4$, $SE = 0.1$, $z = -8.17$, $p < .001$, indicating that participants were more accurate on repeat trials ($M = .97$) than on switch trials ($M = .93$). As we did for RTs, we then added the reward × physical presence of money interaction to the model, which was not significant, $\chi^2(2) = 1.58$, $p = .454$.

Pooled Analysis

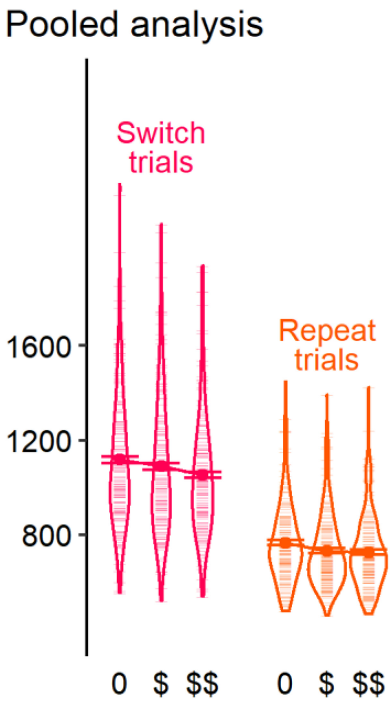
To provide our best estimate of the dose–response relationship between reward value and cognitive performance, we present an *individual participant data meta-analysis* (Borenstein et al., 2009, p. 316). In this analysis, we included all studies reported in the main text of this article. We used the same analyses as before, but we now also included five dummy variables to model potential differences between the four independent datasets (i.e., Experiments 1a, 1b, and the two between-subjects conditions of Experiment 2). This meta-analysis was not preregistered; *p*-values should be interpreted with caution.

Results

RTs

Pooled data are summarized in Figure 5. The main effect of reward was significant, $\chi^2(2) = 37.42$, $p < .001$. Specifically, on average, people were faster in medium-reward than in no-reward blocks, $b = -30$, $SE = 8$, $t(150.9) = -3.73$, $p < .001$, and they were faster in extreme-reward blocks than in medium-reward blocks, $b = -21$, $SE = 9$, $t(147.6) = -2.49$, $p = .014$. The main effect of trial type was also significant, $b = -173$, $SE = 7$, $t(154.4) =$ -23.86, $p < .001$. There was no significant reward value × trial type interaction, $\chi^2(2) = 5.31$, $p = .070$. That said, the decrease in RT between medium-reward and extreme-reward blocks seemed somewhat more pronounced on switch trials than on repeat trials, $b = 14$, $SE = 7$, $t(500.3) = 2.16$, $p = .031$.

Figure 5
Reaction Times (ms) as a Function of Reward and Trial Type



Note. Error bars indicate within-subjects confidence intervals (Cousineau, 2005). Light horizontal bars indicate individual subjects' means. 0 = no reward; $ = medium reward; $$ = extreme reward. See the online article for the color version of this figure.

Accuracy

We found no significant main effect of reward, $\chi^2(2) = 3.99$, $p = .136$. There was an effect of trial type, $b = 0.5$, $SE = 0.0$, $z = 11.3$, $p < .001$, indicating that people were more accurate on repeat trials ($M = .97$) than on switch trials ($M = .93$). The reward value × trial type interaction was not significant, $\chi^2(2) = 0.49$, $p = .784$.

Discussion

When considering all experiments together, we find no evidence for an inverted U-shaped relationship between reward value and performance. Instead, people typically performed better when they could earn greater amounts of money, even when this amount was extreme.

General Discussion

Our findings showed that both medium and extreme rewards increased performance. So, in general, we find no evidence that extreme rewards make people overly rigid or overly flexible during task switching. As an exception to this rule, Experiment 2 showed the anticipated inverted U-shaped relationship—that is, medium rewards increased, but extreme rewards decreased, performance. The inverted U was evident only when the money that could be earned was placed in full view of the participant. Moreover, the inverted U emerged only on repeat trials.

Our experiments thus show that the dose–response relationship between reward value and cognitive performance may follow an inverted U shape (for similar findings in motor tasks, see Chib et al., 2012; Lee & Grafton, 2015; for similar findings in other cognitive tasks, see Ford et al., 1985; Short & Sorrentino, 1986). Our research contributes to the literature in two further ways:

First, our findings suggest that visual reminders of the rewards at stake —here, in the form of the money that can be earned—may be a necessary condition for choking under pressure to occur during cognitive tasks. Though novel, this suggestion may be reconciled with mainstream models of choking under pressure. Specifically, models of choking under pressure suggests that extreme rewards may trigger task-irrelevant thoughts (e.g., "I really need to perform well now, otherwise I miss out on that money"), which take up working memory capacity, which in turn reduces the capacity that is available for carrying out the task (Beilock & Carr, 2005; Beilock et al., 2004; Bijleveld & Veling, 2014). Such *distraction theory*, however, is agnostic regarding how these task-irrelevant thoughts are triggered. Our findings suggest that task-irrelevant thoughts do not appear out of thin air—rather, they may be triggered by visible reminders of what is at stake (Anderson et al., 2011; Bijleveld et al., 2011b; Rusz et al., 2020). In addition, our findings suggest that visual reward cues may harm performance through low-level visual processes (e.g., oculomotor capture by reward cues, Watson et al., 2019). This possibility constitutes an important avenue for further research.

The possibility that reward cues trigger choking under pressure affords a new look at the experimental protocol that is often used to induce choking under pressure in the laboratory (Beilock & Carr, 2001; Beilock et al., 2004; Boere et al., 2016; Ramirez & Beilock, 2011). In this protocol, the experimenter explains to participants that they will earn money only if they perform 20% better than they had previously and that some other participants' payment also depends on their performance. In addition, the experimenter sets up a video camera and explains that the recordings will be shown to "some professors and teachers" from the area, "who are interested in understanding the mechanisms behind good performance" (Ramirez & Beilock, 2011). Although this protocol differs from ours, there are important similarities: both protocols include visual reminders of the importance of performing well (i.e., either a video camera or money on the table) and both include the explicit presence of another person (i.e., either the experimenter delivering scripted instructions or the experimenter taking away money). Our findings suggest that these aspects may be key working ingredients, in that they may be necessary conditions for rewards to impair performance.

Second, the predicted inverted U only emerged on repeat trials. If we interpret this finding in terms of metacontrol models (Eppinger et al., 2021; Hommel, 2015), extreme rewards seem to have biased people's control state toward flexibility. Although this bias facilitates performance on switch trials, it also impairs people's ability to maintain a stable task representation, increasing distractibility and impairing performance on repeat trials. The latter idea resonates with the aforementioned models of choking under pressure that assume a key role for distraction (Beilock et al., 2004).

Relation to Research on Social Facilitation

Our speculation that the physical presence of another person may be a necessary condition for rewards to impair performance is related to classic research on *social facilitation*. In the 1960s, Zajonc proposed that the presence of others increases *arousal* (or *drive*) and that arousal, in turn, enhances the emission of the *dominant response*, that is, the response that is most likely to occur given a certain situation (Zajonc, 1965; Zajonc & Sales, 1966). Zajonc thus predicted that the presence of other people facilitates performance in situations in which the dominant response is correct (e.g., during easy or well-practiced tasks), but impairs performance in situations in which the dominant response is not correct (e.g., during hard or novel tasks).

Though with some qualifications, research generally supported Zajonc's predictions (Bond & Titus, 1983). However, the psychological and physiological mechanisms that mediate social facilitation effects are still subject to debate (Belletier et al., 2019; Geen, 1989; Seitchik et al., 2017). In that regard, it is worth mentioning Harkins' (2006) approach, who advocated that understanding social facilitation requires a fine-grained analysis (a "molecular analysis") of the processes that lead to good performance on a given task. Harkins conducted such a fine-grained analysis for the Remote Associates Task (RAT), in which people are confronted with three words, and are asked to come up with a word that is associated with all three. Harkins concluded that, on the RAT, the presence of other people triggers people to invest more effort into generating words that are closely associated with either of the three initial words. This extra effort helps people to quickly find the correct answer on easy triads (e.g., *daisy*, *tulip*, *vase* → *flower*), but leads them astray on difficult triads (e.g., *force*, *line*, *mail* → *air*).

At first sight, findings from Experiment 2 are inconsistent with the literature on social facilitation reviewed above. After all, this literature suggests that performance impairments are more likely to emerge on more difficult tasks (or trials). By contrast, we found that the presence of other people, combined with extreme rewards, impaired performance on repeat trials, which are comparatively easy (e.g., they result in far shorter RTs than switch trials). Although we can explain our findings based on metacontrol models, more research is needed to examine the circumstances under which the presence of other people can impair performance on (comparatively) easy tasks. A systematic approach, akin to Harkins (2006), would likely be informative.

Relation to the Debate on the Efficacy of Monetary Rewards

Our research is also related to the broader debate about whether monetary rewards are useful tools to increase people's performance (Durham & Bartol, 2012; Gerhart & Fang, 2015; Grant & Shin, 2012). On one side of this debate, most classic motivation theories suggest that rewards are useful tools to intensify and direct behavior. For example, goal-setting theory predicts that rewards increase *goal commitment* and thus intensify goal striving (Locke et al., 1988). Expectancy theories suggest that the *value* (of the goal) is a core predictor of achievement-related choices (Atkinson, 1964; Porter & Lawler, 1968), including choices of whether to invest effort. Motivational intensity theory suggests that rewards should increase *potential motivation*, or the maximum level of effort that people are willing to invest (Brehm & Self, 1989). All these predictions are largely consistent with how incentives are studied and understood by economists (e.g., Laffont & Martimort, 2009). In sum, there is ample reason to expect that rewards should generally have positive effects on effort and performance.

On the other side of this debate, at least three lines of research suggest that rewards can also produce unwanted outcomes. First, research in the domain of self-determination theory suggests that monetary rewards may harm intrinsic motivation, because rewards may thwart people's need for autonomy (Deci et al., 1999). More recently, however, self-determination researchers have found that rewards can also support intrinsic motivation (e.g., when rewards support people's need for competence; Gerhart & Fang, 2015). Second, research from management science and economics suggests that the effectiveness of monetary rewards hinges on the criteria that are used to reward people (Holmstrom & Milgrom, 1994; Kerr, 1975; Muller, 2018). In turn, choosing good criteria is difficult (if not impossible) in practice (Holmstrom & Milgrom, 1994; Thorndike, 1949), which is why incentives sometimes have unwanted or "perverse" effects. Third, as described in this article, monetary rewards may cause *choking under pressure*.

The present research informs the latter debate, as it supports the ideas that (a) choking under pressure may not be the default outcome, even when incentives are extreme, and (b) choking under pressure, if it happens, may be driven by physical distractors in the performance environment. That said, we note that there are other reasons (that are independent of the present research) why monetary rewards may not always lead to enhanced performance in practice, for example, at work.

Limitations

First, in this research, we used only a single task, that is, a rewarded task-switching task. We chose this task because it aligns with prior research in cognitive psychology and neuroscience, in which the task-switching paradigm has often proven useful. However, we note that cognitive tasks in real-life settings (e.g., at work and at school) often have more complex instructions and often require a greater variety of skills. Although both positive and negative effects of reward on performance have been shown to emerge in real life, we do not know whether our findings generalize to organizational and educational settings.

Second, a limitation of Experiment 2 was that in the control condition, there were no additional objects on the table, besides the computer monitor and the keyboard (Figure 3). So, the two conditions did not only differ in the presence versus absence of reward cues, but also in their perceptual richness. Thus, we cannot exclude explanations based on perceptual richness for the pattern of findings in Experiment 2.

Conclusion

Popular science writers often caution against the use of monetary rewards, usually by loosely speculating about the potential side effects of rewards (Kohn, 1993; Pink, 2011). Our research paints a more nuanced and more optimistic picture. We conclude that monetary rewards may trigger choking under pressure, perhaps especially when people are continuously reminded of those monetary rewards. However, this does not happen by default: monetary rewards—even when they are extreme—may well boost, rather than harm, performance on mental tasks.

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