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Rewards boost sustained attention through higher effort: A value-based decision making approach

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A B S T R A C T

Maintaining sustained attention over time is an effortful process limited by finite cognitive resources. Recent theories describe the role of motivation in the allocation of such resources as a decision process: the costs of effortful performance are weighed against its gains. We examined this hypothesis by combining methods from attention research and decision neuroscience. Participants first performed a sustained attention task at different levels of reward. They then performed a reward-discounting task, measuring the subjective costs of performance. Results demonstrated that higher rewards led to improved performance (Exp 1–3), and enhanced attentional effort (i.e. pupil diameter; Exp 2 & 3). Moreover, discounting curves constructed from the choice task indicated that subjects devalued rewards that came at the cost of staying vigilant for a longer duration (Exp 1 & 2). Motivation can thus boost sustained attention through increased effort, while sustained performance is regarded as a cost against which rewards are discounted.

1. Introduction

The capacity to sustain attention while performing a monotonous task has been studied for many decades (Mackworth, 1956). Prevailing theories describe deteriorating performance as a function of task demand, where demand can either be too high, draining the necessary cognitive resources (resource theory: Grier et al., 2003; Warm, Parasuraman, & Matthews, 2008), or too low to maintain arousal (underload theory: Manly, Robertson, Galloway, & Hawkins, 1999; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). Although these approaches successfully explain the effects of external task factors, they may present an overly mechanistic view of sustained attention that is not governed by high-level decision making, and so fail to take into account psychological drives such as motivation.

Resource theories propose that sustaining high performance relies on a limited pool of cognitive resources that shrinks with time-on-task (Warm et al., 2008). Failures in attention are attributed to diminishing resources when one has to maintain alertness over a long duration. Underload models on the other hand posit that the monotonous nature of sustained attention tasks makes performance prone to intrusion by task-unrelated thoughts (Manly et al., 1999; Robertson et al., 1997). Failure to detect task-critical signals results from the occurrence of such off-task epochs.

Although there is evidence for both accounts, neither theory completely explains observed behavior. The resource depletion hypothesis assumes that participants are fully committed and are always giving their maximal effort (Nicholls, Loveless, Thomas, Loetscher, & Churches, 2015), while the underload hypothesis cannot explain why participants subjectively find extended task performance increasingly effortful (Warm et al., 2008).

More recent theories propose that performance is subject to the dynamic allocation of processing resources to task-related and alternative cognitive processes (effort allocation theory: Kurzban, Duckworth, Kable, & Myers, 2013; Thomson, Besner, & Smilek, 2015). How resources are assigned to task performance depends on a cost-benefit analysis where the costs of task performance are weighed against the expected value of its outcomes (Kurzban et al., 2013). Better performance would be expected when a task carries higher value (e.g. through providing rewards: Braver et al., 2014), while behavioral decline would be expected if performance becomes more costly (e.g. due to fatigue: Boksem & Tops, 2008). A few studies have examined the effects of motivation and reward on sustained attention performance (Bergum & Lehr, 1964; Bonnefond, Doignon-Camus, Hoeft, & Dufour, 2011; Esterman, Reagan, Liu, Turner, & DeGutis, 2014; Horne & Pettitt, 1985), but it is still unclear if performance levels are determined via cost-benefit analysis.

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The current study was inspired by decision neuroscience studies on the cost of expending effort on task performance (Botvinick, Huffstetler, & Mcguire, 2009; Kurniawan et al., 2010; Prevost, Pessiglione, Metereau, Clery-Melin, & Dreher, 2010; Treadway, Buckholtz, Schwartzman, Lambert, & Zald, 2009) and how such expenditure is avoided when one is presented with a choice (Kool, Mcguire, Rosen, & Botvinick, 2010; McGuire & Botvinick, 2010). The subjective costs of effort can be quantified by evaluating effort discounting – a tendency to devalue rewards when effort is required to obtain them (Massar, Libedinsky, Weiyan, Huettel, & Chee, 2015; Prevost et al., 2010; Westbrook, Kester, & Braver, 2013). When choosing between a large reward, obtained in exchange for the deployment of some effort or a smaller reward obtained at no cost of effort, we tend to prefer the latter. The reward we are willing to accept (i.e. how much the reward value is discounted) reflects the perceived cost of effort.

Here, we evaluated how this type of cost-benefit decision affects our capacity to sustain attention. First, we examined whether higher reward would improve performance and increase effort exertion in accordance with the effort allocation framework. Second, we determined whether performance was perceived as a cost by having participants consider exchanging task performance for monetary reward. We found support for these predictions in three experiments. When rewards were available, we observed improved performance and pupillometric evidence for increased attentional effort exertion. At the same time, participants discounted rewards when a longer duration of task performance was required.

2. Experiment 1

2.1. Methods

2.1.1. Participants & procedure

Twenty-five subjects (9 females, mean age = 22.72 years, *SD* = 2.7) were recruited. Previous research on reward effects in sustained attention indicated large effect sizes ranging between Cohen's d of 0.84–1.47 in a between-subjects design (Esterman et al., 2014). From power analysis, it follows that a sample size of 9–24 subjects per group would be sufficient to detect such effects. We decided on a sample size of 25 in a within-subjects design with data collection continuing until the target sample size was reached. Due to technical error one participant was removed from the sample at the analysis stage. Participants performed a sustained attention task under three different reward conditions in which they could earn 0, 1 or 10¢ for fast responses. It was expected that higher incentives would lead to better performance, indicative of higher effort investment.

Subsequently, the idea that effort investment would result from a cost-benefit analysis was directly examined using a discounting task. The discounting task is a widely used method in economic research that allows estimating the subjective value that an individual assigns to a monetary reward, taking into account the (non-monetary) costs that are involved in acquiring the reward. We expected that if participants would consider sustained attention performance as costly, they would discount the value of a given reward, if it would be contingent upon performance of a longer duration of the PVT task. The discounting task consisted of a monetary choice task, followed a choice implementation (see below). Participants were reimbursed based on their performance in the reward runs of the sustained attention task, and their selected reward in the choice task. The procedure was approved by the National University of Singapore Institutional Review Board and participants signed informed consent prior to participation.

2.1.2. Motivated vigilance task

The Motivated Vigilance Task is an adaptation of the Psychomotor Vigilance Test (PVT; Dinges & Powell, 1985), which is a 10-min sustained attention task where participants make a button press as quickly as possible upon the appearance of a running millisecond counter (Fig. 1A). These stimuli were separated by uniformly distributed inter-trial intervals that ranged from 2 to 10 s. Participants performed one baseline run without reward, followed by two runs in which participants were rewarded if their responses were faster or equal to the median RT achieved in the baseline run. Par-

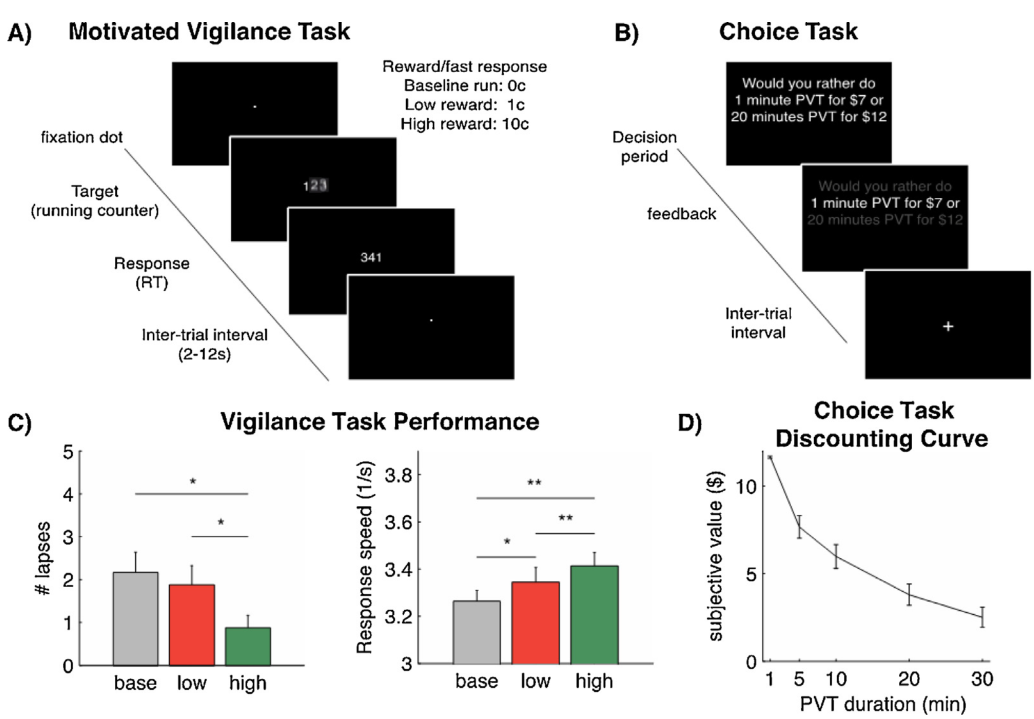

Fig. 1. Experiment 1: Schematics of a trial in (A) the Motivated Vigilance Task and (B) the Choice Task. (C) Vigilance performance under baseline, low and high reward conditions with (left) lapses of attention and (right) response speed. (D) Discounting curve in the choice task. (Error bars denote ± 1SEM; +p < 0.1, *p < 0.05, **p < 0.01).

ticipants received 1¢ per fast response in the low reward run and 10¢ per fast response in the high reward run. The order of the low and high reward runs was counterbalanced across-subjects. Attentional performance was quantified as the number of attentional lapses (responses with RT > 500 ms) and as mean response speed (1/RT) per run. These metrics are considered the most sensitive performance indicators for this task (Basner & Dinges, 2011).

2.1.3. Discounting task

In the discounting procedure, first the subjective cost of performance was determined through a choice task (Weber & Huettel, 2008; see Fig. 1B). Participants were presented with pairs of monetary offers (ranging from $1 to $12). Each choice pair consisted of one low reward option (variable magnitude), that was available in return for a short duration PVT (1 min), and an option that offered a higher reward ($12) for a longer duration PVT (5, 10, 20 or 30 min). After each choice, the monetary reward for low reward option was adjusted following a staircase titration method (i.e. increased if the long duration option was chosen and decreased if the short duration was chosen). This procedure was iterated for six trials per duration, after which the indifference point was determined as the average of the largest amount for which the subject chose the short duration option and the smallest amount for which the subject chose the long duration option. This procedure typically yields stronger discounting of reward values with higher levels of effort (Libedinsky et al., 2013; Massar et al., 2015; Westbrook et al., 2013).

2.1.4. Choice implementation

To establish incentive compatibility (i.e. incentivizing subjects to express their true preference in the choice task), one choice trial was randomly selected for implementation. The participant would receive the monetary amount that he/she had chosen on that trial, and was required to perform the PVT for the associated duration of time. In order to ensure subjects based their choices on the costs of task performance and not on whether they would receive their reward sooner or later (i.e. delay discounting), they were instructed that they would need to stay in the lab for a fixed duration of 30 min. During this period, they would perform the PVT for the chosen duration, and spend the remaining time resting. Hence, the total duration after the discounting task was 30 min for all participants.

2.2. Results

2.2.1. Motivated vigilance task

In line with the effort regulation hypothesis, there was a significant decrease in the number of lapses with increasing reward ($F(2,46) = 4.32$, $p = 0.019$, $\eta_p^2 = 0.158$), Response speed increased with increasing reward ($F(2,46) = 12.57$, $p < 0.001$, $\eta_p^2 = 0.353$). Speed increased from baseline to low reward runs ($F(1,23) = 4.72$, $p = 0.040$, $\eta_p^2 = 0.170$), and additionally from low to high reward runs ($F(1,23) = 12.35$, $p = 0.002$, $\eta_p^2 = 0.342$; Fig. 1C).

The change in performance with progressing time-on-task was quantified by fitting linear regression models to each run of the vigilance task, using response speed as the dependent measure. Negative slopes indicate that response speed declined over time in all conditions (Baseline mean slope = −0.18, $SD = 0.17$; t-test against 0: $t(23) = 4.96$, $p < 0.001$, 95% CI = [−0.254, −0.104]; low reward mean slope = −0.15, $SD = 0.11$, $t(23) = 6.41$, $p < 0.001$, 95% CI = [−0.199, −0.102]; high reward mean slope = −0.14, $SD = 0.16$, $t(23) = 4.13$, $p < 0.001$, 95% CI = [−0.205, −0.068]), with no difference between conditions ($F(2,46) = 0.66$, $p = 0.52$, $\eta_p^2 = 0.028$).

2.2.2. Discounting task

Participants discounted the value of rewards according to duration of task performance ($F(4, 92) = 82.94$, $p < 0.001$, $\eta_p^2 = 0.783$). Subjective values monotonically decreased with increasing task duration indicating that prolonged performance of the PVT was considered a cost against which rewards were discounted (Fig. 1D).

2.3. Discussion

Experiment 1 showed that reward value influences both task performance and the willingness to engage in task performance for a specified duration. In line with the Effort Allocation theory, these findings show that participants are able to improve performance if the task carries sufficient value, and conversely, that reward value is discounted if more costly (longer duration) task performance is required.

3. Experiment 2

A further prediction from the effort allocation account is that higher task value would result in the allocation of more processing resources to task performance. This was tested using pupillometry. Pupil diameter is known to reflect arousal and attentional effort, and it scales with task difficulty (Bradshaw, 1967; Kahneman & Beatty, 1966), potentially through noradrenergic activity (Gilzenrat, Nieuwenhuis, & Jepma, 2010; Varazzani, San-Galli, Gilardeau, & Bouret, 2015) Moreover, recent studies have indicated that pupil diameter decreases with time-on- task and that this reduction is related to task disengagement over time (Hopstaken, van der Linden, Bakker, & Kompier, 2014). We therefore expected performance improvement in the PVT associated with increased reward to be accompanied by pupil dilatation. We additionally predicted that pupil size would decrease with time-on-task.

3.1. Methods

3.1.1. Participants & procedure

A new sample of 25 participants was recruited (10 females, mean age = 22.72 $SD = 3.09$). Participants performed the same experimental procedure as in Experiment 1, but now pupil diameter was monitored through eye-tracker during PVT performance. Data from one participant was excluded from analysis due to technical error.

3.1.2. Pupillometry

Pupil diameter was monitored using a Tobii X60 eye-tracker (Tobii AB, Danderyd, Sweden). Data were sampled at 60 Hz and corrected offline for blinks and artifacts by linear interpolation. Pupil diameter was determined in the 1-s window preceding stimulus onset, and individual z-scores ($[\text{diameter}_{\text{trial n}} - \text{mean}_{\text{diameter}}]/\text{stdev}_{\text{diameter}}$) were calculated across all PVT runs. Average score was calculated per PVT run for each subject. Two participants did not have complete pupillometry data and were excluded from this analysis.

3.2. Results

3.2.1. Behavior

As in Experiment 1, lapses decreased with increasing reward ($F(2,46) = 5.93$, $p = 0.005$, $\eta_p^2 = 0.205$; baseline = low reward: $F(1,23) = 0.23$, $p = 0.634$, $\eta_p^2 = 0.010$; low reward > high reward: $F(1,23) = 7.40$, $p = 0.012$, $\eta_p^2 = 0.244$). Response speed increased as a function of reward ($F(2,46) = 21.28$, $p < 0.001$, $\eta_p^2 = 0.481$; baseline < low reward: $F(1,23) = 4.99$, $p = 0.036$, $\eta_p^2 = 0.178$; low reward < high reward: $F(1,23) = 24.39$ $p < 0.001$, $\eta_p^2 = 0.515$, Fig. 2A). Furthermore, participants significantly discounted the value of rewards according to the proposed task duration in the choice task ($F(4,92) = 35.15$, $p < 0.001$, $\eta_p^2 = 0.604$, Fig. 2B).

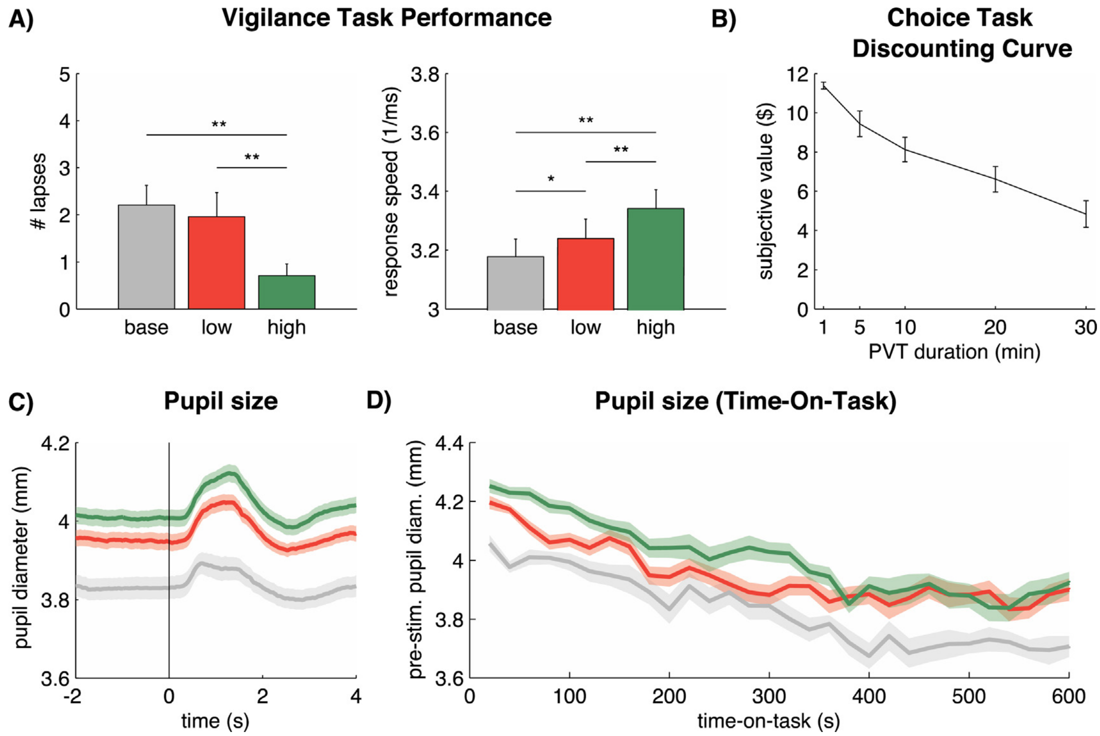

Fig. 2. Experiment 2: (A) Vigilance performance under baseline, low and high reward conditions with (left) lapses of attention and (right) response speed. (B) Discounting curve in the choice task (Error bars denote ± 1SEM; +p < 0.1, *p < 0.05, **p < 0.01). (C) Stimulus locked pupil size in the baseline (light grey), low reward (red), and high reward conditions (green). (D) Pre-stimulus pupil size as a function of time-on-task (Shaded error-bars denote ±1 within-subjects SEM).

3.2.2. Pupillometry

Pupil diameter increased as a function of reward ($F(2,42) = 11.15$, $p < 0.001$, $\eta_p^2 = 0.347$; baseline < low reward: $F(1,21) = 8.85$, $p = 0.007$, $\eta_p^2 = 0.296$; marginal increase from low reward to high reward: $F(1,21) = 3.37$, $p = 0.080$, $\eta_p^2 = 0.138$, Fig. 2C). This increase in pupil diameter was interpreted as indicating that greater physiological effort was exerted during reward runs.

3.2.3. Time-on-task analysis

Similar to Experiment 1 time-on-task effects were calculated by fitting linear regressions for each PVT run with response speed and pupil size as dependent variables and time-on-task as a regressor. For response speed negative slopes were found in all conditions (Baseline mean slope = −0.17, $SD = 0.16$ t-test against 0: $t(23) = 5.13$, $p < 0.001$, 95% CI = [−0.237, −0.100]; low reward mean slope = −0.088, $SD = 0.15$, $t(23) = 2.85$, $p = 0.009$, 95% CI = [−0.152, −0.024]; High reward mean slope = −0.082, $SD = 0.15$, $t(23) = 2.78$, $p = 0.011$, 95% CI = [−0.143, −0.021]), with marginal difference between reward conditions ($F(2,46) = 3.20$, $p = 0.05$, $\eta_p^2 = 0.122$).

Follow-up paired samples t-tests showed a marginally more negative slope in baseline compared to low reward $t(23) = 2.03$, $p = 0.054$, 95%CI = [−0.163, 0.002]; no difference in slope between low reward and high reward: $t(23) = 0.17$, $p = 0.87$, 95%CI = [−0.077, 0.066], significantly more negative slope in baseline compared to high reward $t(23) = 2.16$, $p = 0.04$, 95%CI = [−0.170, −0.004].

Similarly, for pupil diameter negative slopes were found for all runs (baseline: mean slope = −0.38, $SD = 0.26$), one-sample t-test against 0: $t(21) = 6.94$, $p < 0.001$, 95% CI = [−0.491, −0.264]; low reward mean slope = −0.31, $SD = 0.30$, $t(21) = 4.79$, $p < 0.001$, 95% CI = [−0.441, −0.174 high reward: mean slope = −0.38, $SD = 0.38$, $t(21) = 4.68$, $p < 0.001$, 95% CI = [−0.544, −0.209], with no difference between reward conditions ($F(2,42) = 0.74$, $p = 0.485$, $\eta_p^2 = 0.034$, Fig. 2D).

3.3. Discussion

The behavioral results of Experiment 2 clearly replicate the findings of Experiment 1: performance improved with increasing reward, and subjective reward value was discounted with increasing task duration. Pupillometric data additionally demonstrated that overall pupil size was larger throughout rewarded task runs, indicative of higher attentional effort.

4. Experiment 3

To verify that the increased pupil diameter, as was found in the reward runs in Experiment 2, was indicative of greater attentional effort rather than increased arousal associated with the availability of higher rewards, we performed a control experiment where a random reward condition was included. In this condition, rewards equal to the high reward condition were available, but were provided randomly instead of being related to reaction time.

4.1. Methods

Twenty-six participants (15 females, mean age = 23.04, $SD = 3.25$) performed three runs of the MVT task. As in Experiments 1 and 2 the first run was a baseline run, in which no rewards were provided. The second and third runs were the high reward and random reward runs (in counter balanced order). In the high reward run, participants received 10¢ rewards for every fast response. In the random reward run, they were instructed that they would receive 10¢ rewards at random times, not dependent on performance. In both runs the delivery of a reward was indicated by the target stimulus turning green after a response was made. During all runs, pupil diameter was continuously monitored. Due to technical error, two participants were excluded from analysis.

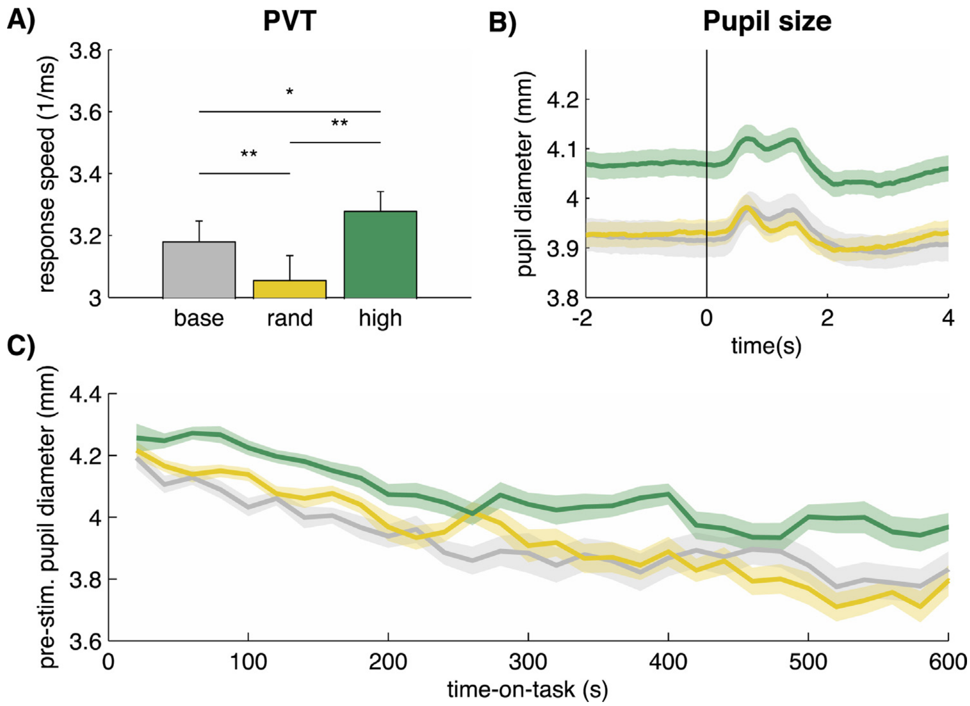

Fig. 3. Experiment 3: (A) Vigilance performance as determined by response speed under baseline, random and high reward conditions (Error bars denote ± 1SEM; +p < 0.1, *p < 0.05, **p < 0.01). (B) Stimulus locked pupil size in the baseline (light grey), random reward (yellow), and high reward conditions (green). (C) Pre-stimulus pupil size as a function of time-on-task (Shaded error-bars denote ±1 within-subjects SEM).

4.2. Results

4.2.1. Behavior

Significant differences in performance were found between MVT runs (run main effect; lapses: $F(2,46) = 7.85$, $p = 0.001$, $\eta_p^2 = 0.254$; response speed: $F(2.46) = 19.11$, $p < 0.001$, $\eta_p^2 = 0.45$). A planned contrast showed that the number of lapses did not differ between baseline and high reward run: $F(1,23) = 2.29$, $p = 0.144$, $\eta_p^2 = 0.090$; but response speed improved from the baseline to high reward run: $F(1,23) = 7.24$, $p = 0.01$, $\eta_p^2 = 0.24$. In contrast, poorer performance was found in the random reward run compared to baseline (lapses: $F(1,23) = 9.22$, $p = 0.006$, $\eta_p^2 = 0.286$; response speed: $F(1,23) = 16.17$, $p = 0.001$, $\eta_p^2 = 0.41$, Fig. 3A).

4.2.2. Pupillometry

Pre-stimulus pupil diameter showed a main effect of run ($F(2.46) = 5.92$, $p = 0.005$, $\eta_p^2 = 0.21$). This effect was driven by an increase in pupil diameter in the high reward run compared to baseline ($F(1,23) = 7.14$, $p = 0.01$, $\eta_p^2 = 0.24$). Crucially no increase in pupil diameter was found when rewards were delivered at random as compared to the baseline ($F(1,23) = 0.077$, $p = 0.78$, $\eta_p^2 = 0.003$, Fig. 3B).

4.2.3. Time-on-task analysis

As in Experiments 1 and 2, response speed decreased with time-on-task in all conditions (Baseline mean slope = −0.14, $SD = 0.16$, t-test against 0: $t(23) = 4.37$, $p < 0.001$, 95% CI = [−0.213, −0.076]; random reward mean slope = −0.17, $SD = 0.19$, $t(23) = 4.42$, $p < 0.001$, 95% CI = [−0.249, −0.090]; high reward mean slope = −0.15, $SD = 0.13$, $t(23) = 5.80$, $p < 0.001$, 95% CI = [−0.200, −0.095]), with no difference between conditions ($F(2,46) = 0.22$, $p = 0.81$, $\eta_p^2 = 0.009$).

For pre-stimulus pupil diameter, there was a significant difference in time on task slope between conditions ($F(2,46) = 4.80$, $p = 0.013$, $\eta_p^2 = 0.17$, Fig. 3C). A significantly stronger decrease in pupil diameter was found in the random reward condition (mean random slope = −0.51, $SD = 0.23$) compared to the baseline condition (Mean baseline slope = −0.30, $SD = 0.36$; $t(23) = 3.14$, $p = 0.005$, 95% CI = [0.071, 0.34]). The high reward condition (mean high slope = −0.40, $SD = 0.17$) did not differ from baseline ($t(23) = 1.30$, $p = 0.21$, 95% CI = [−0.060, 0.265]).

4.3. Discussion

Results of Experiment 3 replicated those obtained in Experiment 2, demonstrating that rewards improve performance and increase attentional effort. Crucially, an increase in pupil diameter was only present when rewards were contingent on good performance (high reward condition) but not when high reward was provided at random (random reward condition).

4.4. Cross-experiments correlational analysis

We examined whether there was any relation between performance in the PVT task and the level of discounting in the choice task. We extracted the area under the discounting curve (AUC; Myerson, Green, & Warusawitharana, 2001) as an individual measure of discounting for all participants from Experiment 1 and 2, and correlated this with the difference in response speed between the high reward PVT run and the baseline run. A significant positive correlation was found ($r(46) = 0.31$, $p = 0.032$, Fig. 4), indicating that participants who showed the strongest improvement in performance in the PVT discounted the least in the choice task. A similar correlation between discounting AUC and reward benefit in pre-stimulus pupil diameter (Experiment 2: high-baseline) was not significant ($r(20) = 0.005$, $p = 0.98$).

4.5. False start response analysis

To examine whether the increase in response speed in the rewarded PVT runs was accompanied by more liberal response threshold (i.e. speed-accuracy trade-off) we analyzed the number

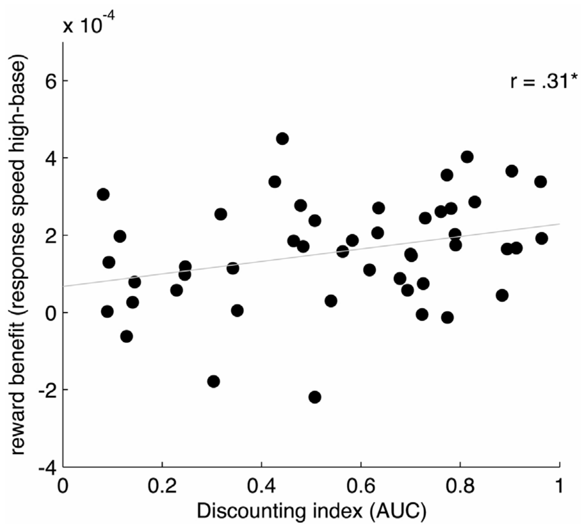

Fig. 4. Correlation between area under the discounting curve (AUC) in the choice task and performance benefit in the PVT.

of responses that occurred before the onset of the target stimulus (false starts; Fig. 5).

In Experiment 1 no significant difference in the number of false starts was found between reward conditions ($F(2,46) = 2.02$, $p = 0.144$), although numerically fewer false starts were found in rewarded runs (mean baseline = 2.33, $SD = 3.19$; low reward = 1.6, $SD = 2.10$; high reward = 1.2, $SD = 1.41$).

In Experiment 2 false starts occurred significantly less in the rewarded runs (mean low reward = 0.63, $SD = 0.71$, high reward = 0.54, $SD = 0.98$) compared to baseline (mean = 1.42, $SD = 1.25$; $F(2,46) = 6.64$, $p = 0.003$, $\eta_p^2 = 0.224$).

In Experiment 3 no significant difference were found in the number of false starts ($F(2,46) = 1.33$, $p = 0.28$; mean baseline = 1.46, $SD = 1.35$; random reward = 2.17, $SD = 2.55$; high reward = 1.58, $SD = 1.59$).

This pattern of data demonstrates that the increase in response speed in the rewarded runs did not come at the expense of a more impulsive response strategy. Rather, participants showed an overall improvement of performance when reward was at stake (Manohar et al., 2015).

5. General discussion

We found that sustained attention performance improved in anticipation of greater reward. This was accompanied by increased pupil size in rewarded task runs, indicative of increased allocation of attentional resources to task performance (Kahneman & Beatty, 1966). In the choice task, participants discounted monetary rewards that were contingent on longer-duration task performance, indicating that prolonged task performance is considered a cost against which rewards are devalued (Botvinick et al., 2009; Prevost et al., 2010).

These results follow the predictions of the Effort Allocation theory and suggest that sustained attention performance is substantially influenced by the motivational value of the task. Extending earlier studies that reported improved sustained attention performance with reward (Bergum & Lehr, 1964; Esterman et al., 2014; Horne & Pettitt, 1985) we demonstrated that improvement was associated with increased attentional effort. This increase in effort allocation with reward is not predicted by Resource Theories which assume that maximal attentional effort is constantly applied (Grier et al., 2003).

In addition to the overall improvement in performance and increase in pupil size in the rewarded runs of the Motivated Vigilance Task, marked decline in performance with time-on-task was evident under all conditions. Here, our results do not unequivocally align to a single theory. The performance decline could reflect depletion of resources with time-on-task, even when more resources are initially allocated to the task (Esterman et al., 2014). Alternatively, performance decrement could reflect voluntarily withdrawal of attentional resources as performance became more effortful with time. The latter interpretation would be in line with the effort allocation account (Kurzban et al., 2013; Thomson et al., 2015). In contrast to a previous study, we found that subjects could uphold their performance better over time-on-task in rewarded runs compared to baseline (Esterman et al., 2014). However, this was only the case in one out of three experiments (Exp2). Further, this difference in reward conditions was not mirrored in pre-stimulus pupil diameter, where the time-on-task decrement was consistently present in all runs. We therefore refrain from any strong conclusions with respect to the subjects' ability to counter the time-on-task effect as a function of reward motivation.

One of the central tenets of Effort Allocation models is that the choice to deploy resources in task performance is based on a cost-benefit analysis in which effort is weighted against expected reward (Kurzban et al., 2013). This idea was more explicitly tested in the discounting task where participants made prospective decisions about how much experimental time to spend on task performance relative to task-unrelated activities. Participants discounted the value of available rewards when the proposed duration of the task increased, suggesting that they found longer tasks increasingly costly. This interpretation concurs with observations that subjective workload increases with longer task duration (Grier et al., 2003; Warm et al., 2008). The current data concur with recent studies on effort-based decision-making, which observe that the level of cognitive demand affects preference and valuation in a variety of tasks (Kool et al., 2010; Massar et al., 2015; McGuire & Botvinick, 2010; Westbrook et al., 2013). More specifically, our data show that the subjective valuation of available rewards depends on the relative division of time between effortful performance and rest (Kool & Botvinick, 2014).

A further prediction of Effort Allocation theory would be that when more resources are allocated to task performance, fewer

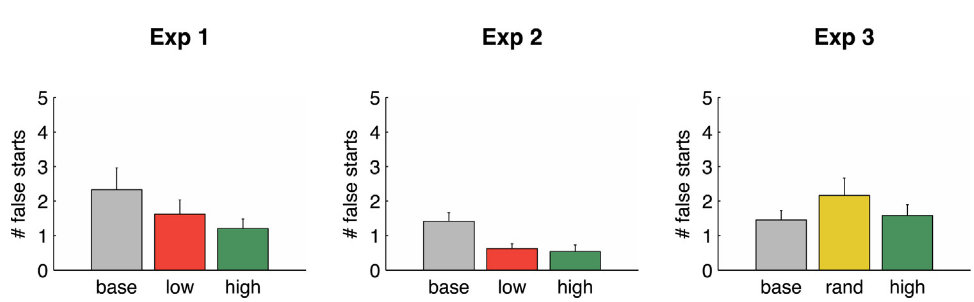

Fig. 5. False start responses in the Motivated Vigilance Task in Experiment 1–3. Error bars denote ± 1SEM.

resources should be available for task-unrelated cognition. This hypothesis was not directly tested in the current study, but other studies that have measured the occurrence of task-unrelated thoughts (TUT) indeed indicate that TUTs happen less frequently when participants are more motivated to perform, either intrinsically or through monetary incentives (Mrazek et al., 2012; Seli, Cheyne, Xu, Purdon, & Smilek, 2015).

In conclusion, the current study clearly establishes that effort allocation in sustained attention performance is affected by the motivational value of the task, and that the subjective value of reward is discounted by the effort required to receive the reward. These findings cannot easily be explained by traditional Resource and Underload theories without additionally assuming some level of volitional control over resource allocation. By including this control as a factor in sustained attention models, we are moving away from explanations viewing the brain as a "capacity limited machine". Rather, this allows us to accommodate findings from a variety of different subfields (e.g. motivation, emotion and decision neuroscience), opening the door to a richer and more accurate model of sustained attention performance.

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