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Reward Reveals Dissociable Aspects of Sustained Attention

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Although reward is known to have a powerful influence on performance, its effects on the ability to continuously sustain performance over time are poorly understood. The current study examines multiple measures of sustained attention (accuracy and variability) and their decrements over time, while introducing reward in the form of a monetary incentive or the promise of early completion. Compared with unrewarded participants, rewarded participants demonstrated greater overall accuracy and lower reaction time variability. However, rewarded and unrewarded participants displayed nearly identical decrements in performance over time, suggesting that these aspects of sustained attention are far less malleable by enhanced effort. This study helps to resolve conflicting models of sustained attention as it reveals that some aspects of performance are due to motivational lapses whereas others are due to the depletion of cognitive resources that cannot be easily overcome.

Keywords: sustained attention, vigilance, reward, motivation

Sustaining a moderate level of attention over time is critical to the performance of most everyday activities. Nevertheless, our ability to sustain attention can be undermined by many factors, including distraction, fatigue, and boredom. The degree to which these failures of sustained attention reflect motivational lapses or resource limitations has been debated extensively and remains controversial (e.g., Grier et al., 2003; Kurzban, Duckworth, Kable, & Myers, 2013). Further, although motivation and reward have been shown to enhance performance in a number of cognitive domains including attention, it is unclear whether and how performance on sustained attention tasks is impacted by such factors. The current study attempts to address these questions by examining how different behavioral metrics of sustained performance are enhanced by increasing motivation via multiple types of rewarding incentives.

Two prominent theories of sustained attention make distinctly different predictions regarding the effects of reward and motivation (e.g., Grier et al., 2003; Pattyn, Neyt, Henderickx, & Soetens, 2008). The "underload" theory proposes that difficulties sustaining attention are due to disinterest, boredom, and/or underarousal—factors that may be attenuated by reward and motivation. For example, the mindlessness model attributes declines in performance to failures of a supervisory attentional system to direct attention to tasks as they become monotonous (Manly, Robertson, Galloway, & Hawkins, 1999; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). Considering that reward and motivation have been shown to engage this supervisory attentional system (e.g., Jimura, Locke, & Braver, 2010; Pessoa, 2009), the mindlessness model predicts that these factors should enhance sustained attention. On the other hand, resource theory proposes that sustained attention worsens over time (i.e., vigilance decrement) due to the depletion of a limited pool of attentional resources (Grier et al., 2003; Parasuraman & Davies, 1977; Parasuraman, Warm, & Dember, 1987). This theory proposes that sustaining attention is effortful and that any factor that puts greater demands on attentional resources will elicit a larger vigilance decrement (Parasuraman, 1979; Parasuraman et al., 1987; Warm, Parasuraman, & Matthews, 2008). Insofar as the incentive of reward can lead to enhanced evoked neural responses across task-positive networks (e.g., Engelmann, Damaraju, Padmala, & Pessoa, 2009), resource theory predicts that reward would be associated with, if anything, reduced performance over time as enhanced activation may lead to faster depletion of limited attentional resources in continuous performance tasks (CPTs; e.g., Smit, Eling, & Coenen, 2004). Thus, in contrast to underload models, resource models predict that sustained attention performance should not improve with increased reward and motivation.

One explanation for these opposing views of sustained attention is that they emerge from different tasks and use different measures to operationalize sustained attention. Support for the mindlessness

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model typically relies on brief (<10 min) not-X continuous performance tasks in which participants respond to the majority of stimuli and withhold responses on rare target trials (e.g., the sustained attention to response task, or SART; Robertson et al., 1997). These tasks measure failures to inhibit responses on target trials (commission errors, interpreted as acts of "mindlessness") and corresponding moment-to-moment fluctuations in reaction times (RTs) but are often insensitive to, or do not report, vigilance decrements. On the other hand, resource theorists generally use more lengthy vigilance tasks (>30 min) that involve responding to rare, perceptually difficult target events (although shorter tasks have been used, see below, e.g. Helton & Warm, 2008). These tasks are highly sensitive to performance declines over time (e.g., Davies & Parasuraman, 1982), but because responses are infrequent, other subtle aspects of sustained attention such as RT fluctuations (Castellanos et al., 2005; Di Martino et al., 2008; Esterman, Noonan, Rosenberg, & DeGutis, 2013; Rosenberg, Noonan, DeGutis, & Esterman, 2013) are not reliably measured. Neurally, these two models have associated different brain networks with sustained performance. On the one hand, mindlessness theorists have shown that activity in the default mode network is associated with both errors on sustained attention tasks and mind wandering (e.g. Christoff, Gordon, Smallwood, Smith, & Schooler, 2009). On the other hand, resource theorists have linked activity in a right-hemisphere-dominant frontal-parietal system to vigilance decrements (e.g., Langner & Eickhoff, 2013; Shaw et al., 2013). Recent attempts to integrate these neural models have suggested that optimal performance relies on intermediate levels of activity or emerges from a balance between the two networks (Esterman et al., 2013; Esterman, Rosenberg, & Noonan, 2014).

Several recent studies have attempted to resolve this theoretical controversy, often by critically comparing these two types of CPTs. Such studies have shown that, in contrast to a strict mindlessness model, increasing difficulty or engagement with factors such as stimulus novelty (Head & Helton, 2012), complexity (Helton & Russell, 2011a), degradation (Parasuraman et al., 2009) and spatial uncertainty (Helton, Weil, Middlemiss, & Sawers, 2010) increases errors and does not reduce task-unrelated thoughts (e.g., Head & Helton, 2012). Further, longer not-X CPTs do evoke vigilance decrements similar to traditional CPTs (e.g., Parasuraman et al., 2009), and such decrements are associated with similar declines in cerebral blood flow to frontal-parietal attentional regions (Langner & Eickhoff, 2013; Shaw et al., 2013). Together, these studies cast doubt on a strict mindlessness model, suggesting that sustained performance failures are not simply due to task disengagement in other mental activities nor to the overly simple cognitive/perceptual demands of certain tasks. They further demonstrate that the mechanism underlying sustained attention failures are not dependent on task type (not-X vs. X CPTs). Finally, these studies suggest that there may be an important dissociation between overall performance and vigilance decrements (Helton & Warm, 2008; Parasuraman, Warm, & See,1998; Smit et al., 2004). Specifically, Helton and Warm (2008) proposed, "The mindlessness model has some merit in regards to understanding overall signal detection rates, but not in accounting for the vigilance decrement" (p. 23). Using functional magnetic resonance imaging (fMRI), our own work has suggested that failures of sustained attention can be precipitated by both mindlessness (as indexed by high default mode activity) and depletion (as indexed by low attention network activity) and that these depletion errors are more likely to occur later in the vigil (Esterman et al. 2013). Taken together, attempts to resolve these theories suggest that some failures to engage attention are due to suboptimal motivation or to a high opportunity cost in performing these potentially "aversive" tasks (Kurzban et al., 2013), whereas other failures are due to task difficulty and whether the necessary resources are "used up" and thus unavailable. Experimental manipulations of motivation and reward represent a novel behavioral method to identify why different types of attention failures occur, as well as refine and synthesize these two prominent theories.

To gain a more complete understanding of the effect of reward on sustained attention and tease apart these two models, we used a type of CPT (gradual onset continuous performance task, gradCPT; Esterman et al., 2013; Rosenberg et al., 2013; see details below) that has been shown to be sensitive to measures used by both mindlessness (overall accuracy and reaction time fluctuations) and resource theorists (vigilance decrements) in a short period of time (10 min). This not only allowed a more comprehensive examination of the effects of reward on sustained attention but also enabled the predictions of mindlessness and resource models to be directly tested in the same task. Participants performed the gradCPT without reward or with one of three different reward conditions: (a) Participants were told that the task would end sooner if they performed better, (b) participants were provided with explicit monetary rewards based on better performance, or (c) participants were provided these same monetary rewards with periodic feedback during the task. If motivational factors are responsible for sustained attention failures, as mindlessness theory suggests, reward should attenuate these errors and improve performance. If sustained attention failures are due to the depletion of limited cognitive resources that cannot be easily replenished, as resource theory suggests, reward should not attenuate such failures and may even result in a larger vigilance decrement.

Method

In the current study, we used a between-groups design to assess the effects of reward on aspects of sustained attention. We chose this design to eliminate likely order effects of switching from rewarded to unrewarded blocks, as well as the cumulative effects of fatigue. To determine the number of participants, we surveyed the previous sustained-attention literature and used power analyses (G*Power 3), setting power to .95, a value commonly used in behavioral research (Kraemer & Thiemann, 1987). In particular, because the vigilance decrement is the most novel aspect of performance differences with respect to reward, we focused on studies that tested for vigilance decrement differences. We found five comparable studies (Caggiano & Parasuraman, 2004; Helton & Russell, 2011b; Helton & Warm, 2008; Morgan, Johnson, & Miles, 2014; Parasuraman, 1979). Sample size was chosen based on large effect sizes in these previous studies, in which the between subjects studies in particular estimated ~18 subjects per group. We used this N as a guideline for each experiment.

Participants

Seventy-four participants were recruited from Northeastern University and Boston University in Boston, Massachusetts, and participated in one of four experiments (~18 per experiment). Initially, 36 participants were randomly assigned to Experiment 1 (18 total, five men, mean age = 19.94, *SD* = 1.31) or Experiment 2 (18 total, eight men, mean age = 20.22, *SD* = 2.24) in order to compare behavior without a reward (Experiment 1) with a time reward (see Procedure below; Experiment 2). One participant was excluded from Experiment 2, as the participant explicitly indicated doubt that reward would actually be received. An additional 20 participants were recruited for Experiment 3A (nine men, mean age = 21.10, *SD* = 2.94) to assess the behavioral effects of monetary reward as an extension of Experiment 2. Finally, in Experiment 3B, another 18 participants were recruited to replicate the effects of reward in Experiment 3A, when including periodic feedback in the same monetary reward paradigm (five men, mean age = 20.06, *SD* = 1.47). This study was approved by the VA Boston Healthcare System institutional review board, and written consent was obtained from all participants. Baseline payment for participation was $30.

Paradigm and Stimuli

The current version of the gradCPT contained 20 round, gray-scale photographs, half of them depicting mountain scenes and half of them depicting city scenes (Esterman et al., 2013). It is notable that the gradCPT uses naturalistic stimuli that differ from most other traditional or not-X CPTs, which use simple or abstract stimuli (although see Head & Helton, 2012; Helton & Russell, 2011a; Parasuraman et al., 2009). The use of these more complex, naturalistic stimuli has been argued on the one hand to reduce monotony and mindlessness and boost motivation, and, on the other, to deplete performance faster. In the gradCPT, the scene images were randomly presented with 10% mountain and 90% city scenes without allowing an identical scene to repeat on consecutive trials. Scene images gradually transitioned from one to the next, in a linear pixel-by-pixel interpolation, with each transition occurring over 800 ms. Participants were instructed to press a button for each city scene and withhold responses to mountain scenes. Verbal instructions given to participants emphasized response accuracy without reference to speed. However, given that the next stimulus would replace the current stimulus in 800 ms, a response deadline was implicit in the task. The images were presented on a 15-in. MacBook Pro using the Psychophysics Toolbox in MATLAB and subtended a diameter of approximately 4.8° of visual angle.

Procedure

Before completing the gradCPT, participants in each experiment were familiarized with each of the 20 scene images (labeled as *city* or *mountain*), followed by two 30-s practices.

Experiment 1. No reward. Participants were simply advised of the length of the task (10 min) and asked to perform as accurately as possible.

Experiment 2. Time reward. Participants were advised that the length of the task would be directly influenced by their performance; task length was said to vary between 6 and 20 min. Participants were advised that their accurate performance, in the form of both correct responses to city scenes and correctly withholding responses to mountain scenes, would lead to shorter task duration. No other information or specifics regarding the relationship between task performance and task duration were communicated to the participant. Actual duration was 10 min for all participants. Because this motivational method was novel, we asked each participant to subsequently rate on a scale from 1 (*strongly disagree*) to 6 (*strongly agree*) whether knowing that performance influenced the duration of the task motivated his or her performance.

Experiment 3A. Monetary reward. Participants were informed that the task would last 10 min and that a performance-based reward would be calculated incrementally for each trial: plus or minus $0.01 for correct and incorrect presses to cities respectively, and plus or minus $0.10 for correct and incorrect non-presses to mountains respectively. Participants were advised that the minimum bonus award was $0.00, the maximum award was approximately $14.00, and that the task was coded so that simply pressing or failing to press to 100% of the trials would lead to a bonus of $0.00 (because the task had ~10% mountains). After these instructions were given and understood, a third 30-s practice was completed, and a hypothetical bonus amount was displayed on-screen at its conclusion. Actual reward amount was similarly displayed at the end of the 10-min task, and administered to participants at the end of the session. Average winnings were $11.53 (*SD* = $1.76).

Experiment 3B. Monetary reward with feedback. Participants completed the identical monetary reward experiment (Experiment 3A) with one addition. Feedback was presented every 2 min above and below the central stimulus for 800 ms (one trial) indicating the amount of money accumulated thus far in the experiment (similar to other studies with trial-based or block-based reward feedback, e.g., Engelmann & Pessoa, 2007; Engelmann et al., 2009). Thus, feedback was presented four times during the experiment (at min 2, 4, 6, and 8), as well as at the end of the experiment. Average winnings were $11.52 (*SD* = $1.35).

Behavioral Analyses

Reaction time. RTs were calculated relative to the beginning of each image transition such that an RT of 800 ms indicated a button press at the moment image n was 100% coherent and not mixed with other images. A shorter RT indicated that the current scene was still in the process of transitioning from the previous scene, and a longer RT indicated that the current scene was in the process of transitioning to the subsequent scene. For example, an RT of 720 ms would indicate a button press at the moment of 90% image n and 10% image $n - 1$, and so forth. On rare trials with highly deviant RTs (before 70% coherence of image n and after 40% coherence of image $n + 1$) or multiple button presses, an iterative algorithm maximized correct responses. The algorithm first assigned unambiguous correct responses, leaving few ambiguous button presses. Ambiguous presses were then assigned to an adjacent trial if one of the two trials had no response. If both adjacent trials had no response, the press was assigned to the closest trial unless one trial was a no-go target, in which case participants were given the benefit of the doubt that they correctly omitted. If there were multiple presses that could be assigned to any one trial, the fastest response was selected. Slight variations to this algorithm yielded highly similar results, as most button presses showed a 1:1 correspondence with presented images.

RTs were used to calculate mean RT and RT variability (coefficient of variation [CV] = standard deviation of RT/mean RT), as well as vigilance decrements in RT variability (see below).

Accuracy. Trials in which participants correctly inhibited a button press to mountain scenes were considered hits (correct omissions). Trials in which participants erroneously responded to mountains were considered misses (commission errors). Trials in which participants failed to respond to city scenes were considered false alarms (omission errors). D' was calculated as a measure of accuracy that incorporated both types of trials.

Time-on-task effects. Time-on-task effects, or vigilance decrements, were measured by calculating 2-min windows around RT variability and accuracy measures of interest (CV and d'), where the first window included 0–2 min and the last included 8–10 min. A 2-min window size was selected such that reliable estimates of commission errors were possible, as an average of 15 no-go trials occurred in each window. Time-on-task effects were evaluated between-subjects in mixed 2 × 5 analyses of variance (ANOVAs) comparing No Reward with each reward experiment as a between-subjects factor and Time as a within-subjects factor. In particular, the interaction term of this model reflects different decrement rates in the two reward conditions. In addition, a linear slope (computed as rate of change per minute) was calculated for each subject. *T*-tests were used to contrast slopes with 0 (to determine whether there was significant linear change over time), as well as to compare slopes across experiments.

Subject outliers. When pooled across all experiments, those participants who performed outside of three standard deviations from the mean on any of the dependent measures were excluded. This resulted in the elimination of three (4%) participants: one in Experiment 2 and two in Experiment 3A.

Results

Experiment 1: No Reward

Experiment 1 provides a baseline of comparison for the other three experiments.

Overall performance. Participants overall d' was 2.58 (commission errors on 36% of mountain trials and omission errors on 3.9% of city trials), similar to previously obtained results (Esterman et al., 2013). Mean RT was 722 ms, reflecting that participants responded about 78 ms before the current scene was 100% cohered.

Time-on-task effects. Participants exhibited performance decrements in d' and RT stability (increased variability) over time. D' decreased linearly over time (linear slope $= -0.060$/min; $t_{17} = 3.43$, $p < .01$). Correct RT variability (CV) increased over time (linear slope = 3.4 ms/min; $t_{17} = 2.44$, $p < .05$).

Experiment 2: Time Reward

Overall performance. Motivation to finish sooner had significant effects on overall performance accuracy and RT variability (see Figure 1). Participants were more accurate ($d' = 3.41$; $t_{32} = 2.61$, $p < .05$ vs. Experiment 1; $\eta^2 = 0.18$) and less variable (CV; $t_{32} = 2.38$, $p < .05$; $\eta^2 = 0.15$). This was not due to overall changes in response speed, as mean RT was not significantly different from Experiment 1 (708 vs. 722 ms, $p > .4$).

Time-on-task effects. In contrast to overall performance, vigilance decrements were observed that were not significantly different from Experiment 1 in d' and CV (see Figure 2). Interactions between reward and time were not significant for d' ($F_{4,128} = 1.38$, $p > .2$, $\eta^2 = 0.008$) or for CV ($F_{4,128} = 0.56$, $p > .6$, $\eta^2 = 0.004$). D' decreased linearly over time (linear slope $= -0.067$/min; $t_{15} = 3.50$, $p < .01$). This slope was not significantly different from Experiment 1 (-0.067 vs. -0.060; $p > .7$; $\eta^2 = 0.003$). Numerically, the slope was slightly steeper in the time reward condition.

RT variability followed the same pattern. CV increased linearly over time (linear slope = 3.3ms/min; $t_{15} = 2.29$, $p < .05$). This slope was not significantly different from Experiment 1 (3.3 vs. 3.4; $p > .9$; $\eta^2 = 0.0002$).

Posttask ratings. Because this was a novel motivator in the literature, we asked participants to rate the degree to which the instructions motivated performance on a scale from 1 to 6. On average, participants rated the instructions as highly motivating ($M = 5.6$, $Mdn = 6$, range = 4–6).

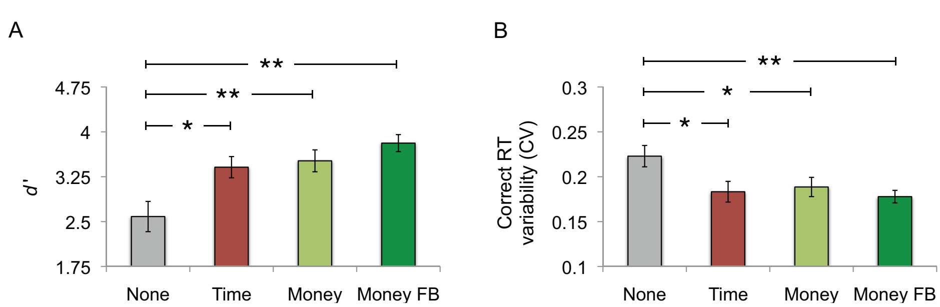

Figure 1. Overall gradual onset continuous performance task (gradCPT) performance in the four reward experiments: Experiment 1, none; Experiment 2, time; Experiment 3A, money; Experiment 3B, money feedback (FB). (A) Response accuracy (d'). Participants in the rewarded experiments (time, money, money FB) exhibited greater discrimination sensitivity than did participants without reward. (B) Reaction time (RT) variability (coefficient of variation [CV]) of correct response trials. Participants in the rewarded experiments (time, money, money FB) exhibited less RT variability than did participants without reward. Error bars reflect standard error of the mean (SEM). * $p < .05$. ** $p < .01$. See the online article for a color version of this figure.

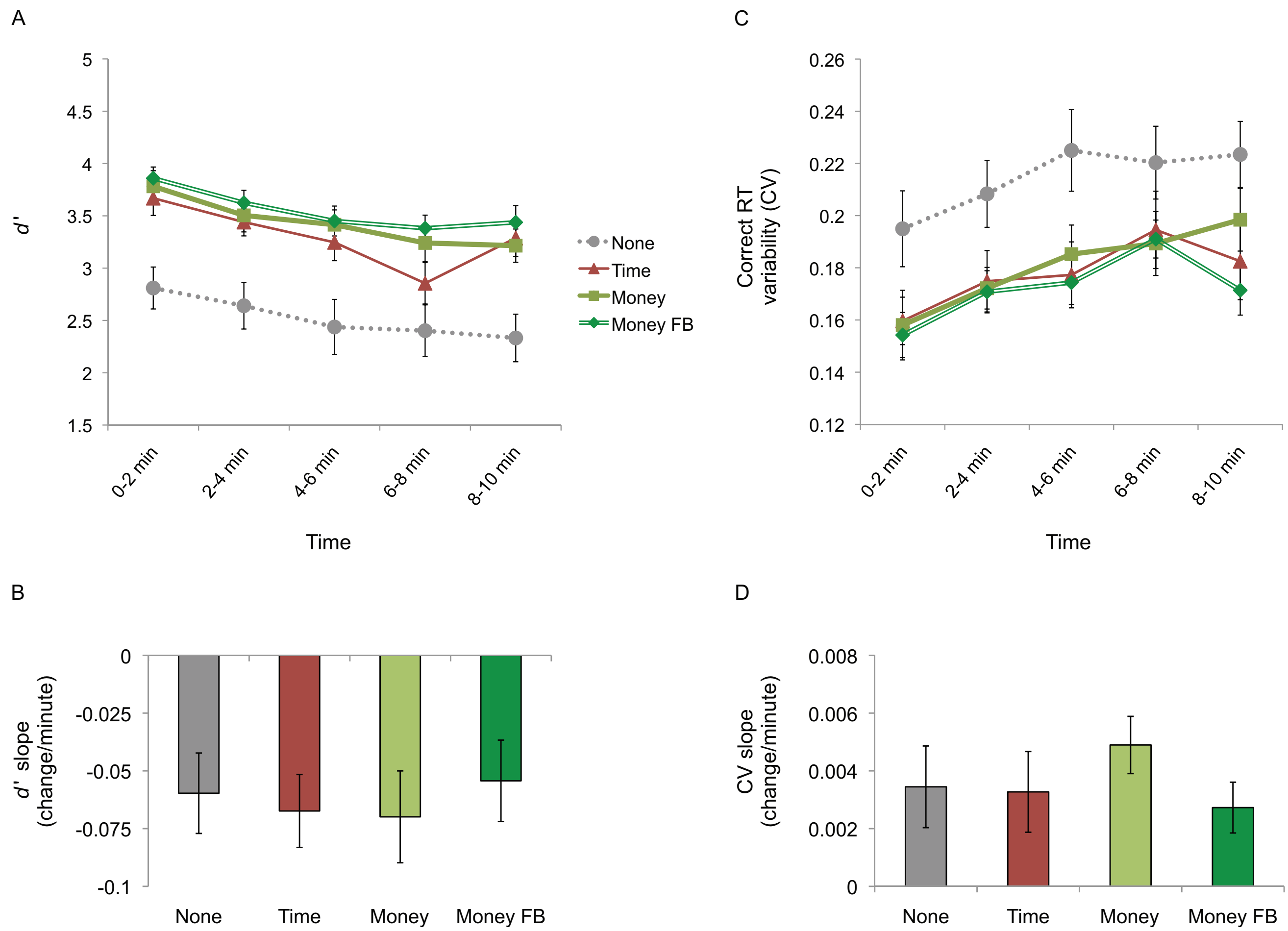

Figure 2. Time-on-task effects: performance across 2-min task intervals and linear slopes of gradual onset continuous performance task (gradCPT) performance. (A) Vigilance decrement in d'. Discrimination sensitivity declines over the 10-min of continuous performance. (B) Linear slopes are equivalent in the four experiments, regardless of reward. (C) Vigilance decrement in correct reaction time (RT) stability (increased variability). RT variability increases over the 10 min of continuous performance. (D) Linear slopes are equivalent in the four experiments, regardless of reward. Error bars reflect standard error of the mean. FB = feedback; CV = coefficient of variation. See the online article for a color version of this figure.

Experiment 3A: Monetary Reward

Overall performance. Similar to the time reward manipulation, the promise of a monetary reward significantly improved overall performance accuracy and RT variability but did not affect the decrements in these measures over time (Figure 1 and Figure 2). Participants were more accurate ($d' = 3.52$; $t_{34} = 2.98$, $p < .01$ vs. Experiment 1; $\eta^2 = 0.21$) and less variable (CV, $t_{34} = 2.14$, $p < .05$; $\eta^2 = 0.12$) than Experiment 1. This was not due to overall changes in response speed, as mean RT was virtually identical to Experiment 1 (727 vs. 722 ms, $p > .7$).

Time-on-task effects. In contrast to overall performance, vigilance decrements were observed that were not significantly different than Experiment 1 in d' and CV (Figure 2). Interactions between reward and time were not significant for d' ($F_{4,136} = 0.18$, $p > .9$, $\eta^2 = 0.001$) or for CV ($F_{4,136} = 0.31$, $p > .8$, $\eta^2 = 0.002$). D' decreased linearly over time (linear slope $= -0.070$/min; $t_{17} = 3.52$, $p < .01$). This slope was not significantly different from Experiment 1 (-0.070 vs. -0.060; $p > .7$; $\eta^2 = 0.004$).

RT variability followed the same pattern. CV increased linearly over time (linear slope = 4.9ms/min; $t_{17} = 4.94$, $p < .01$). This slope was not significantly different from Experiment 1 (4.9 vs. 3.4; $p > .4$; $\eta^2 = 0.02$). If anything, the slope was slightly steeper in the money reward condition, although this did not approach significance.

Experiment 3B: Monetary Reward With Feedback

Overall performance. Similar to the other reward manipulations, reward significantly improved overall performance accuracy and reaction time variability but did not impact the decrements in these measures over time (Figure 1 and Figure 2). Participants were more accurate ($d' = 3.81$; $t_{34} = 4.23$, $p < .01$ vs. Experiment 1;

$\eta^2 = 0.35$) and less variable (CV, $t_{34} = 3.27$, $p < .01$; $\eta^2 = 0.24$) than Experiment 1. Unlike in other reward conditions, there was a trend toward faster response speed vs. Experiment 1 (691 vs. 722 ms, $p < .08$).

Time-on-task effects. In contrast to overall performance, vigilance decrements were observed that were not significantly different than Experiment 1 in $d'$and CV (Figure 2). Interactions between reward and time were not significant for d' ($F_{4,136} = 0.13$, $p > .9$, $\eta^2 = 0.001$) or for CV ($F_{4,136} = 0.92$, $p > .4$, $\eta^2 = 0.006$). D' decreased linearly over time (linear slope $= -0.054$/min; $t_{17} = 3.08$, $p < .01$). This slope was not significantly different from Experiment 1 (-0.054 vs. -0.060; $p > .8$; $\eta^2 = 0.001$).

RT variability followed the same pattern. CV increased linearly over time (linear slope $= 2.7$ms/min; $t_{17} = 3.10$, $p < .01$). This slope was not significantly different from Experiment 1 (2.7 vs. 3.4; $p > .6$; $\eta^2 = 0.01$).

Comparison of Reward Experiments

Overall performance. No significant differences were observed between the three reward experiments. Participants were numerically more accurate (d') in Experiment 3B, although these effects did not reach significance (p values > 0.2). Variability was similar across the three rewards (CV; p values > 0.4). In contrast, mean RT was marginally faster (691 vs. 726 ms, $p = .055$) in Experiment 3B vs. Experiment 3A.

Time-on-task effects. Vigilance decrements in $d'$and CV did not significantly differ across the three reward conditions. Critically, sensitivity (d') slopes were nearly identical (p values > 0.5 for all comparisons). CV slope was numerically higher in Experiment 3A when compared with the other experiments, but this did not reach trend level significance (p values $> .1$) and may have been due to the 8–10-min time point in particular. Importantly, this effect was in the opposite direction of the overall effects of reward to improve performance, as the slope was steeper. In comparing Experiment 3A and 3B in particular, we found that interactions between reward and time were not significant for d' ($F_{4,136} = 0.25$, $p > .9$, $\eta^2 = 0.002$) or for CV ($F_{4,136} = 1.71$, $p > .1$, $\eta^2 = 0.014$).

Discussion

We examined the effects of reward-based motivation on multiple aspects of sustained attention in order to characterize the mechanisms underlying performance failures. Using two types of reward-based motivators across three experiments, we demonstrated that reward enhances overall response accuracy as well as response stability (lower variability). Critically, we also showed a dissociation between the effects of reward on overall performance versus performance decrements over time. Time-on-task effects in RT variability and accuracy appear to be insensitive to motivation. Together, these findings have important theoretical implications for understanding the interaction of reward and sustained attention as well as for models of sustained attention itself.

The finding that reward enhances overall performance accuracy and stability indicates that, on the whole, inaccurate and variable performance does not simply arise from exhausting a limited resource. Instead, "underload" factors, such as boredom, mindlessness, lack of motivation, or high opportunity cost, are important contributors to poor performance. This is consistent with evidence that mind wandering and task-unrelated thoughts are related to performance on similar tasks (Manly et al., 1999; Robertson et al., 1997; Rosenberg et al., 2013; Smallwood et al., 2004), as well as overall performance on traditional CPTs (Helton & Warm, 2008). Motivation likely improves performance by enhancing activity in regions of the supervisory attentional system, such as frontal-striatal circuitry, regions previously shown to mediate the effects of reward on cognition (Pessoa, 2008; 2009). Additionally, motivation may improve performance by suppressing activity in the default mode network (Liddle et al., 2011), a network of regions whose activity is thought to reflect task-unrelated thoughts and mind wandering (Christoff et al., 2009). Finally, reward may help optimize and stabilize performance by promoting a more efficient attentional state ("in the zone") characterized by intermediate levels of activity in both default mode and attention networks (Esterman et al., 2013; 2014).

The finding that performance decrements in accuracy and response stability are resistant to the effect of reward lends credence to the theory that vigilance decrements are the result of the depletion of a limited resource (Warm et al., 2008) that cannot be easily replenished with motivation. This is consistent with previous studies demonstrating a lack of relationship between vigilance decrements and task-unrelated thoughts, as well as strong relationships between perceived effort and vigilance decrements (Grier et al., 2003; Head & Helton, 2012; Helton & Warm, 2008; Warm et al., 2008). This is similar to the strength model of self-control developed by Baumeister and colleagues, which proposed that self-control is a limited resource that requires replenishment (e.g. Baumeister, Bratslavsky, Muraven, & Tice, 1998; Hagger, Wood, Stiff, & Chatzisarantis, 2010). The nature of this purported limited resource has led to a spirited debate in the literature (e.g., Kurzban et al. 2013). One possible mechanism is that limited resources are metabolic (e.g., related to glucose), although evidence is inconclusive, given that administration of glucose can act as a reward itself rather than as replenishment (see Hagger et al., 2010; Kurzban et al., 2013 for discussions). Rather than glucose, another physiological mechanism for vigilance decrements may be subcortical systems involved in fatigue, circadian rhythms, and homeostasis, as vigilance decrements have similar behavioral properties to sleep deprivation (Gunzelmann, Gross, Gluck, & Dinges, 2009). Another possibility is that supervisory attentional control resources, which are needed to maintain task set (e.g., Coull, Frackowiak, & Frith, 1998), require breaks for optimal performance (Ariga & Lleras, 2011). Alternatively, these limited resources may be perceptual in nature, as visual and sensory regions of the brain are subject to habituation and adaptation (Grill-Spector, Henson, & Martin, 2006), which could impair vigilant performance (Gruber, 1964; Scott, 1957). Finally, depletion may represent an inability to maintain an optimal, efficient balance of activity (neither hyper- nor hypoactive) across task-positive, task-negative, and sensory cortical networks (Esterman et al., 2013; 2014).

Together, the dissociation between the overall versus time-on-task effects provides evidence that the mechanism by which motivation enhances overall performance is at least partially independent from the mechanism by which performance declines over time. If the overall reward-related performance enhancement was due to recruitment of the same limited resource responsible for the vigilance decrement, then slopes should have been steeper in the reward conditions because resources would get "used up" more quickly. Instead, our results suggest that resisting momentary mindlessness or task-disengagement may be a different process than maintaining vigilant visual attention over time. This is also consistent with previous models suggesting that overall performance on vigilance tasks is affected by arousal but that the vigilance decrement is not necessarily affected by arousal nor due to decreases in arousal over time (Helton & Warm, 2008; Parasuraman et al., 1998; Smit et al., 2004). Given this framework, our results may indicate that the promise of reward enhances arousal/level of alertness, leading to fewer attentional lapses and fewer fluctuations. However, as the gradCPT is performed continuously, the resources available for supporting sustained attention (both perceptual discrimination and response control) are reduced over time despite enhanced reward-related arousal.

Importantly, reward-based motivators did not consistently lead to faster mean response times, although there was a trend for such an effect in the money reward with periodic feedback (Experiment 3B), which was potentially the most arousing condition. This suggests that the effects of motivation are not dependent on faster or slower mean RT. The absence of an overall reward effect on mean RT is likely due to the fact that both types of trials (go and no-go) were rewarded proportionally and that slower RTs would result in more false alarms, whereas faster RTs would result in more misses. In the context of inhibitory control, this study is the first to show that rewarding both response and response inhibition trials in an equally weighted manner can improve performance on both types of trials (Boehler, Hopf, Stoppel, & Krebs, 2012; Padmala & Pessoa, 2010).

There are several limitations of the current study. It has been argued that not-X CPTs, as opposed to traditional CPTs, measure different types of sustained attention (Helton, 2009; Seli, Cheyne, & Smilek, 2012). Specifically, whereas not-X CPTs measure attentional control over the motor system, traditional tasks are thought to measure sustained perceptual awareness to external stimuli. Despite this concern, others have found similar patterns of vigilance decrements and interactions with stimulus degradation (using more naturalistic stimuli) regardless of task type (Parasuraman et al., 2009), and both types of tasks lead to vigilance related decreases in cerebral blood flow (Shaw et al., 2013). Thus, whereas different aspects of attention may be required given the response probabilities (frequent go or infrequent go), evidence suggests that these types of attention have similar behavioral and neural properties. Future work should determine if the observed dissociation generalizes to "traditional" X-CPT or vigilance tasks that may tap into a different type of attentional control. A related concern regarding not-X CPTs is that one must account for speed–accuracy tradeoffs (Seli et al., 2012; Seli, Jonker, Cheyne, & Smilek, 2013). In the current study, the lack of RT differences between reward conditions confirm that the shift in accuracy was not due to strategic slowing or speeding of RT.

An additional concern is the duration of the current task. It is indeed possible that the effects of reward on vigilance decrements are not observable until reaching a more depleted state that occurs only with additional time on task. For example, using a more traditional vigilance task and longer duration, one study found that monetary reward did attenuate the vigilance decrement, although the decrement required more than 2 hr of task performance to be observed (Sipowicz, Ware, & Baker, 1962). Although the short duration may limit conclusions, it has been shown that vigilance decrements can be observed in short periods of time using traditional CPTs as well (Caggiano & Parasuraman, 2004; Esterman et al., 2013; Helton & Warm, 2008; Rosenberg et al., 2013) and that these behave similarly to long tasks, likely depleting the same mechanism. Further, event rate may be a critical variable affecting the vigilance decrement rather than time-on-task per se (e.g., Parasuraman, 1979). A recent meta-analysis also speaks to this issue, as brain activations associated with sustained attention tasks of wide durations activate qualitatively the same networks (Langner & Eickhoff, 2013). In sum, longer tasks could involve nonlinear changes in performance and interactions with motivation. Nevertheless, the current results demonstrate that although task motivators dramatically improve performance, they cannot attenuate an initial decline (over 10 min) in performance over time.

Another concern regards the salience of the motivators in these tasks. For example, the reward scenario may have become less relevant over time, contributing to the performance decline in these experiments. There are several pieces of evidence that cast doubt on this hypothesis. First and foremost, Experiment 3B demonstrates similar time-on-task effects as the other experiments, when reward reminders are present. Second, subjects in Experiment 2 nearly all reported that they were maximally motivated by the instructions after the experiment was completed. Additionally, if motivation had been forgotten, motivated subjects would have performed like unmotivated subjects as the task progressed. In contrast, in the motivation conditions, subjects maintained their advantage over the condition without motivation. Thus our results demonstrate that motivational enhancements can be sustained, but despite these motivational enhancements, performance decline over time is inevitable. Even assuming the subjects' sustained motivation, motivational salience could change over time for other reasons. For example, as time goes on, the amount of money/time that can be gained or lost diminishes. Thus, the opportunity cost to engage in other task-unrelated mental activities decreases (Kurzban et al., 2013). This leaves open the possibility of a nonresource account of the currently observed dissociation. One potential way to test this opportunity cost versus resource model would be to increase/decrease the reward payoffs with time-on-task and determine whether such changing payoffs influence overall and time-on-task effects.

Finally, although our sample sizes are relatively small for a between-subjects design, we note that the observed null effects of reward on the vigilance decrement were small ($\eta^2 < =.02$). In this case of .02, it would require 97 subjects to detect a significant effect, and this effect is actually in the opposite of the hypothesized direction (it is in fact a nonsignificantly greater decrement over time with reward). Thus, lack of power was not driving our dissociations between the effects of reward on overall versus time-on-task effects in the current study.

The current study has critical implications for resolving a central debate in the sustained attention literature. The results suggest that both mindlessness and resource depletion may play a role in attention failures and can be dissociated by examining different metrics of performance. Additionally, the results have important clinical implications and applications to the study of individual differences. Sustained attention and inhibitory control deficits are common among a range of patients with psychiatric and neurological disorders such as attention-deficit/hyperactivity disorder, anxiety disorders, and dementia (e.g., Barkley, 1997). As such, the experimental approach developed in these studies may have the ability to tease apart whether such deficits and individual differences in attentional ability are due to suboptimal attentional resources or rather due to motivational deficits.

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