SHORT PAPER

Reward motivation normalises temporal attention after sleep deprivation

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Abstract

Preparation of attention facilitates speeded responding at time points with a high probability of target occurrence. Conversely, time points with low target probability are disadvantaged due to lower readiness. When targets are uniformly distributed in time, this effect results in higher readiness after longer preparation times (foreperiods). During sleep deprivation, this temporal bias is amplified, resulting in greater performance decrement when stimuli occur at unfavourable times. In this study, we examined whether reward motivation could modulate this increased temporal bias in response speed. Participants ($n = 24$) performed the psychomotor vigilance task under four reward conditions (0, 1, 5 or 15c per fast response), both after normal sleep (rested wakefulness) and sleep deprivation. To assess temporal preparation (foreperiod-effect), trials were binned based on the lead time prior to target presentation (short foreperiod: 1–6 s; long foreperiod: 6–10 s). As previously observed, the foreperiod-effect (slower reaction time for short foreperiod trials) increased after sleep deprivation. However, this state effect was attenuated with reward, reaching a response speed comparable to that observed in the unrewarded, well-rested condition. The current findings, therefore, suggest that reward improves overall response performance and normalises temporal attention in sleep-deprived individuals.

KEYWORDS
attentional readiness, foreperiod, motivation, reward, sleep deprivation, temporal preparation

1 | INTRODUCTION

Being prepared to respond rapidly is often of crucial importance (e.g. when detecting the brake lights of a car ahead of you in a heavy fog). In such situations, having an expectation of when an important event may occur can help focus attention at material moments in time, and increase readiness to respond. This is particularly important following sleep deprivation (SD), where slow responses can result in catastrophic consequences (e.g. increasing the risk of vehicular accidents; Horne & Reyner, 1999).

In the laboratory, implicit temporal preparation can be investigated using tasks in which participants make speeded responses to targets that are preceded by the appearance of a warning signal at varying time intervals (foreperiod [FP]; Nickerson, 1965). When different FP durations prior to a target are equally likely (uniform distribution), responses are faster when targets follow longer compared with shorter FPs. This phenomenon is termed the FP-effect, and is traditionally thought to reflect the growing attentional readiness with time (Niemi & Näätänen, 1981). As the anticipation period lengthens, there is increasing expectation for an event to occur, given that it has not occurred yet (conditional probability; Nobre, Correa, & Coull, 2007). This FP-effect, therefore, reflects a temporal bias to attend to moments of highest conditional probability for crucial events.

In simple reaction time (RT) tasks target stimuli are often separated by random inter-stimulus intervals (ISIs). For instance, in the

2 of 4

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Sleep
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SASMITA ET AL.

Psychomotor Vigilance Test (PVT)—a standard test for the behavioural effects of SD—targets are preceded by ISIs drawn from a uniform distribution ranging from 2 to 10 s (Dinges & Powell, 1985). Here, ISIs are akin to FPs; although no explicit warning signal is presented, the start of a trial marks the start of the associated preparation period, and is clearly demarcated by the appearance of a fixation dot. Accordingly, responses in the PVT are typically faster when targets follow longer compared with shorter ISIs (Matthews et al., 2017; Tucker, Basner, Stern, & Rakitin, 2009). Interestingly, this FP-effect is amplified after a night of SD (Kong, Asplund, Ling, & Chee, 2015; Massar & Chee, 2015). Specifically, while responses are overall slower after SD, performance impairment was most severe for targets following short ISIs.

In the current study, we examined whether increasing performance motivation can counter the increased temporal bias after SD. Previous studies have found that performance degradation in SD can be reduced by providing motivational incentives (e.g. monetary reward; Horne & Pettit, 1985). Moreover, incentives can reduce the magnitude of the FP-effect in well-rested states (Massar, Lim, Sasmita, & Chee, 2018a). It is presently not known if reward can alter the exaggerated temporal bias in response preparation in the sleep-deprived state.

2 | METHODS

Data from a motivated vigilance task (previously reported in Massar, Lim, Sasmita, & Chee, 2018b) were re-analysed. Participants ($n = 26$, 16 females; mean age [SD] = 22.8 [3.5]) performed four runs of the PVT under different reward conditions, once following a night of rest (rested wakefulness; RW) and another time following SD. Participants underwent both RW and SD conditions, and all reward conditions (within-subjects), with order of conditions counter-balanced between-subjects.

Rested wakefulness and SD nights were conducted in the laboratory. For RW sessions, participants reported to the lab at 21:00 hours and were given a 9-hr sleep opportunity from 22:00 to 07:00 hours (monitored with actigraphy; Actiwatch2, Philips Respironics, Bend, Oregon, USA; mean [SD] total sleep time = 7:26 hr:min [81.8 min]). For SD sessions, participants reported to the lab at 19:00 hours and were kept awake throughout the night under the supervision of a research assistant. Each participant's SD and RW nights were spaced 1 week apart, and the session order was counterbalanced between participants.

In the morning after SD and RW nights, participants performed four runs of the PVT in different reward conditions. Each PVT trial started with a fixation dot in the middle of the screen. Following irregular ISIs (randomly drawn from a continuous uniform distribution ranging from 2 to 10 s), a target appeared in the form of a running millisecond counter. Participants were instructed to respond as quickly as possible to the target. Following response, RT was displayed for a period of 1s before being replaced by a fixation point and the next trial begins. Each PVT run lasted for 10 min, comprising of approximately 80 trials.

Testing sessions began at 08:00 hours for the RW sessions and at 06:00 hours for the SD sessions. Timing of the SD session coincides with the circadian nadir, at which time the effects of prolonged wakefulness are found to be the most pronounced. At that time, participants had been sleep deprived for approximately 22 hr. Participants started with a baseline (no reward) condition from which a response criterion was derived (median RT). In each subsequent run, each fast and accurate response (RT faster than criterion) was rewarded with either low (1c), medium (5c) or high (15c) reward. The order of the rewarded runs was counterbalanced between participants, but was kept consistent across each participants' SD and RW sessions. During testing, PVT runs were administered one after another with minimal breaks in between.

For analysis, trials were binned into targets that appear following short (ISI: 2–6 s) and long (ISI: 6–10 s) FPs. Trials with RT < 150 were excluded, and median RTs for each session run and FP condition were extracted. Two subjects had outlier median RT values in at least one of the conditions (median RT > group mean RT + 3 × SD) and were excluded from further analysis. Median RTs for each FP condition were subjected to a 2 (sleep state: SD versus RW) × 2 (FP: short versus long) × 4 (reward: baseline versus low versus medium versus high) repeated-measures ANOVA. Greenhouse–Geisser corrections were applied whenever the assumption of sphericity was violated. Whenever an interaction was significant, follow-up analyses were done on the FP-effect calculated according to Kong et al. (2015):

FP-effect = median RT of short FP − median RT of long FP

3 | RESULTS

Median RTs in the different FPs, sleep states and reward runs are plotted in Figure 1, upper panel. As expected, overall RT was slower following SD (sleep state main effect: $F_{1,23} = 57.65$, $p < 0.001$, partial $\eta^2 = 0.715$), faster with higher reward (reward main effect: $F_{3,69} = 12.97$, $p < 0.001$, partial $\eta^2 = 0.361$), and faster following long FPs (FP main-effect: $F_{1,23} = 103.00$, $p < 0.001$, partial $\eta^2 = 0.817$).

Central to our investigation, there was a marginal three-way interaction (sleep state × reward × FP: $F_{3,69} = 2.69$, $p = 0.053$, partial $\eta^2 = 0.105$), suggesting reward modulation on the influence of SD on performance following different FPs. Follow-up analyses (Figure 1, lower panels) revealed that in the baseline run, the FP-effect was increased in SD compared with RW ($t_{23} = -2.70$, $p = 0.013$; replicating Kong et al., 2015). With low reward, however, this difference was reduced to a marginal level ($t_{23} = -1.79$, $p = 0.087$). Furthermore, in the medium and high reward runs, the FP-effect was further reduced and was no longer different from RW levels (medium: $t_{23} = 0.21$, $p = 0.840$; high: $t_{23} = -0.79$, $p = 0.438$).

4 | DISCUSSION

We examined how reward influenced temporal preparation after a night of SD. Consistent with previous studies, we found that
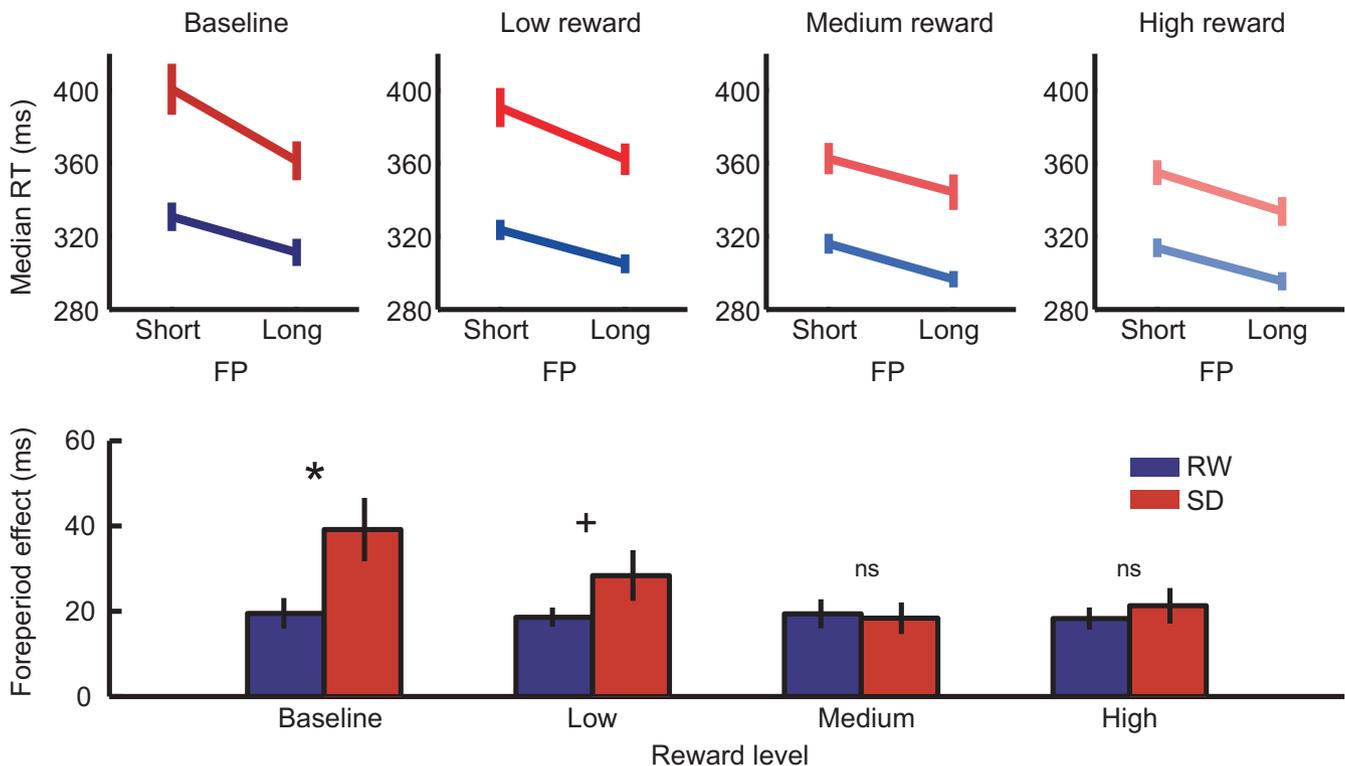
FIGURE 1 Upper panels: median RT following short and long foreperiods (FPs) in the rested wakefulness (RW; blue) and sleep deprivation (SD; red) sessions. Lower panels: FP-effect in the RW (blue) and SD (red) sessions. *$p < 0.05$, +$p < 0.10$

following SD, there was an increase in temporal bias as quantified by the FP-effect (Kong et al., 2015). Interestingly, reward modulated this increase in FP-effect. Notably, increasing the value of reward dampened the amplified FP-effect in SD to a comparable level to performance recorded in the well-rested state.

The FP-effect reflects implicit attentional preparation over time, when target timing is unpredictable. As sustaining a constant level of attentional readiness is metabolically costly, efficient resource allocation is established by biasing attention to time points where events are most likely to occur (i.e. highest conditional probability; Niemi & Näätänen, 1981). In situations where attentional resources are reduced (e.g. SD), reliance on such a resource conservation mechanism is potentially increased (Kong et al., 2015). Thus, periods where targets are least expected (short FPs) are left especially vulnerable to response slowing associated when one is sleep deprived.

In our study, the exaggerated FP-effect that follows SD was attenuated by reward, to reach levels similar to the well-rested state, at the highest reward runs. This suggests that when sufficiently motivated, sleep-deprived individuals may allocate attentional resources more evenly, negating the exacerbated temporal bias in unmotivated conditions. At this point, it is important to note that overall response times in a sleep-deprived state were still significantly slower than when well rested. Therefore, the facility to upregulate attentional resources through reward can soften but not eliminate a source of response slowing in SD.

It has been proposed that the FP-effect may result from an associative learning mechanism (i.e. boosting attention at time points that

are often paired with target appearance through conditioning mechanisms, while inhibiting attention at time points that are surpassed; Los, Kruijne, & Meeter, 2014; Mattiesing, Kruijne, Meeter, & Los, 2017), rather than from conditional probability per se (Vallesi, Arbula, & Bernardis, 2014). This has further implications on how the FP-effect is influenced by the history of FPs in preceding trials (a phenomenon called the sequential effect). Previous research has shown that the sequential effect is affected by SD (Kong et al., 2015) and by motivation (Massar et al., 2018a). The current task structure did not provide a sufficient number of trials to perform a fine-grained analysis on the sequential effect, and was not designed to arbitrate between the different theoretical accounts. Moreover, while it is possible that reward motivation influences the processes of implicit timing directly, we find it more likely that additional control mechanisms are recruited that can act on top of the learned temporal biases (Los & Van Den Heuvel, 2001). Such control mechanisms may serve to maintain higher levels of arousal/alertness throughout the waiting period, and/or by reactively mobilising compensatory resources whenever targets appear at moments of low readiness (i.e. short FPs; Massar et al., 2018a).

In conclusion, SD increases the temporal bias in response preparation, particularly worsening the detriments of incomplete preparation. By increasing the motivation to perform, we have shown that this enhanced temporal bias following SD may be normalised to rested levels. Here, the provision of reward potentially promotes a more even distribution of attentional resources across time.

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