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Dissociable influences of implicit temporal expectation on attentional performance and mind wandering

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ABSTRACT

Mind wandering at critical moments during a cognitive task degrades performance. At other moments, mind wandering could serve to conserve task-relevant resources, allowing a brief mental respite. Recent research has shown that, if target timing is predictable, mind wandering episodes coincide with moments of low target likelihood. Conversely, mind wandering can be avoided at moments when targets are expected. In the current study, we tested whether mind wandering can be guided by implicit temporal expectations when target timing is less predictable. In two experiments (Experiment 1: N = 37, Experiment 2: N = 61), participants performed a sustained attention task in which target events were preceded by a variable pre-target interval (foreperiod). As time passes over the foreperiod duration, implicit target expectation increases, given that it has not yet appeared. In Experiment 1, all foreperiod durations were equally probable (uniform distribution: 2–10 s). This resulted in faster responses when targets were preceded by long compared to short foreperiods (foreperiod-effect). In contrast, mind wandering, assessed by thought probes inserted following short or long foreperiods, did not follow this pattern. In Experiment 2, alterations in the foreperiod distribution (left or right-skewed) resulted in changes in the behavioral foreperiod-effect, but mind wandering was unaffected. Our findings indicate that implicit timing strongly affects behavioral response to target events, but has no bearing on the mind wandering. Contrastingly, mind wandering did correlate with performance deterioration due to fatigue (time-on-task), suggesting that the thought probe method was sufficiently sensitive to behaviorally relevant changes in mental state.

1. Introduction

Mind wandering can be thought of as a temporary disengagement of attention from task performance associated with task-unrelated thoughts or imagery (Smallwood & Schooler, 2015). Off-task cognition can be either voluntary or unintentional (Seli, Risko, Smilek, & Schacter, 2016), and is thought to reflect fluctuations in allocation of attentional resources (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009). Such fluctuations could arise from temporary failures of cognitive control (McVay, Kane, & Kwapil, 2009), insufficient availability of required resources (Helton & Warm, 2008; Thomson, Besner, & Smilek, 2015), or altered prioritization (Kurzban, Duckworth, Kable, & Myers, 2013). Accordingly, mind wandering results in impaired performance in the form of increased error-rates (Poh, Chong, & Chee, 2016; Smallwood, McSpadden, & Schooler, 2007), greater variability in reaction times (McVay & Kane, 2009; Seli, Cheyne, & Smilek, 2013), and poorer memory for task-related material (Smallwood, Baracaia, Lowe, & Obonsawin, 2003; Thomson, Besner, & Smilek, 2013).

1.1. Temporal dynamics of mind wandering

As mind wandering is conceptualized as being not constrained by external task goals, it is thought to be inherently dynamic in nature (Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016). The focus of attention may fluctuate over time as the mind drifts in and out of mind wandering episodes. Moreover, both the content of thought as well as the configuration of associated brain networks are thought to vary dynamically during mind wandering (Andrews-Hanna, Smallwood, & Spreng, 2014; Christoff et al., 2016). While it is widely accepted that mind wandering fluctuates over time, little research has been done to characterize its temporal dynamics. Perhaps the most well studied temporal aspect of mind wandering is the observation that mind wandering episodes become more frequent the longer a participant is

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engaged in task performance (time-on-task effect). This increase in mind wandering is typically accompanied by a decline in attentional task performance, and is thought to reflect the gradual shift of attentional resources away from the primary task (Thomson et al., 2015).

Time-on-task effects are typically measured over the course of minutes (10 min or longer) of task performance. However, it is known that fluctuations in attentional focus and mind wandering can occur at shorter time scales, e.g. over the course of several trials (Esterman, Noonan, Rosenberg, & DeGutis, 2013). Kucyi and Davis (2014) analyzed fluctuations in dynamic functional brain connectivity over 40-second windows, and found that mind wandering covaried with dynamic changes in connectivity in the Default Mode Network (DMN). In another study, mind wandering was found to be associated with behavioral fluctuations in reaction time variability in a Sustained Attention to Response Task (SART). Using these RT variability time courses, it was estimated that on-task and off-task episodes typically alternated in 10 to 20-seconds periods (Bastian & Sackur, 2013). These findings suggest that mind wandering fluctuates at both shorter and longer time courses.

1.2. *Strategic timing of mind wandering*

Interestingly, a recent study showed that the timing of mind wandering can be strategically regulated. In a study by Seli, Carriere, et al. (2018), participants watched a clock that rotated in regular intervals of 20 s, and had to make a button response whenever the clock hand reached the 12 h position. At random intervals, a thought probe was presented, interrogating the subjects' present state of mind. Results showed that participants reported more frequent mind wandering at time periods when no response was required (i.e. when the clock hand was far away from the 12 h position), and less mind wandering closer to moments of a required button press (when the clock hand approached 12 h). Consistent with resource-control accounts of mind wandering (Smallwood & Schooler, 2015; Thomson et al., 2015), the propensity to mind wander may be regulated in accordance to expectations of critical events and task demands. Such tuning-out of attention may reflect a volitional withdrawal of attentional resources at moments of relative unimportance (Kurzban et al., 2013), and may serve to conserve or replenish such resources (Shaw, Finomore, Warm, & Matthews, 2012).

One key feature of the aforementioned task is that the temporal structure is highly regular. Critical events (i.e. the clock hand reaching 12 h) occurred at fixed 20 second intervals, making target timing fully predictable. Explicit temporal expectations under such conditions, allowed participants to strategically take task-contingent cognitive breaks without substantial impairments to task performance (Shaw et al., 2012). In contrast, when target timing is less predictable, it may be more difficult to strategically time the occurrence of cognitive breaks. If a participant engages in mind wandering when a target is presented at an unexpected moment in time, the subject may not be sufficiently prepared to respond. Temporally unpredictable tasks are therefore thought to require more continuous task monitoring, engaging attention-related brain circuits more continuously (Langner & Eickhoff, 2013). It may therefore be expected that fluctuations in on and off-task cognition may differ in temporally predictable versus unpredictable tasks (Unsworth & Robison, 2018).

1.3. *Implicit timing and performance*

While temporally unpredictable tasks are devoid of explicit cues that inform about target timing, such tasks are not free from the influence of temporal expectations (Nobre, Correa, & Coull, 2007). In fact, the distributional properties of target timing, and the passage of time itself, give rise to a set of implicit temporal expectations that influence performance. When target timing is uniformly distributed within a given range (i.e. targets are equally likely to appear at any moment in time), temporal uncertainty is maximal. However, as time from the start of a trial passes without the target appearing, the conditional probability of target occurrence (given that it has not appeared yet) increases, reducing the temporal uncertainty. Accordingly, the observer's implicit anticipation is higher after a longer lead time before target presentation (long foreperiod), compared to a shorter lead time (short foreperiod).

The behavioral consequences of these implicit temporal expectations are well documented. Early research has shown that reaction times are faster when targets are preceded by longer foreperiods (the foreperiod effect; Bertelson & Tisseyre, 1968; Nickerson, 1965). This is accompanied by ramping EEG activity over frontal brain regions, indicating increasing attentional readiness with longer foreperiod duration (CNV: Contingent Negative Variation; Loveless, 1973; Niemi & Näätänen, 1981). Later research has confirmed these findings, and has demonstrated that performance improvement with higher temporal expectation also generalize to response accuracy and perceptual processing speed (Thomaschke, Wagener, Kiesel, & Hoffmann, 2011; Unsworth, Spillers, Brewer, & McMillan, 2011; Vangkilde, Coull, & Bundesen, 2012).

Different mechanisms have been proposed to underlie these behavioral foreperiod effects. Strategic accounts posit that an active monitoring system tracks the conditional probability of target occurrence, and adjusts the allocation of attentional resources to moments in time with the highest target probability (Alegria & Delhaye-Rembaux, 1975). In contrast, conditioning accounts propose that attentional strength is adjusted on a trial-by-trial basis, through associative learning mechanisms (Los, Knol, & Boers, 2001). Attention at time points that are more often associated with a target is reinforced, while attention at time points that are bypassed (which happens more often for short foreperiods) is inhibited. While evidence for and against both account exists (Los et al., 2001; Los, Kruijne, & Meeter, 2014; Vallesi, Lozano, & Correa, 2013; Vallesi & Shallice, 2007), they seem to converge on a common outcome: observers are less ready to respond to external stimuli when implicit temporal expectations are low.

1.4. *Current study*

Although performance is clearly influenced by implicit temporal expectations, it is not known whether these behavioral effects reflect fluctuations in the balance between on-task and off-task attentional focus. Similar to the observation in an explicit timing task (Seli, Carriere, et al., 2018), moments of low attentional readiness (at short foreperiods), may also be characterized by higher occurrence of mind wandering. Participants could allow themselves to mind wander more during the earlier part of each trial when the probability of target occurrence is low. Consequently, long RTs for targets presented after short foreperiods may reflect disengagement from the task, or mind wandering. Conversely, at longer foreperiods, when target likelihood is high, greater attention would result in faster and more consistent RTs. The primary aim of the current study was to test for this.

Participants performed a sustained attention task in which targets were separated by variable foreperiods (uniform distribution: 2–10 s). Thought probes were inserted at various moments to assess the momentary level of mind wandering. Similar to targets, thought probes were preceded by variable foreperiods, to allow for the examination of mind wandering episodes at short versus long foreperiod durations. Following the findings of temporal expectancy dependent mind wandering in explicit timing tasks (Seli, Carriere, et al., 2018), we expected that mind wandering would also follow temporal expectations. Accordingly, we hypothesized that participants would report greater amount of mind wandering at periods of low temporal expectation (i.e. short foreperiods) than at periods of high temporal expectation (i.e. long foreperiods).

Our second goal was to examine whether mind wandering episodes in the context of implicit timing were under voluntary control. Off-task cognition may occur unintentionally, despite effort and motivation to stay on task. Alternatively, a participant may voluntarily allow their thoughts to wander off from the externally set task goals (intentional mind wandering; Dixon, Fox, & Christoff, 2014; Seli, Carriere, & Smilek, 2014). If implicit temporal attention reflects a strategic allocation of attentional resources based on conditional probability, we would expect that this allocation would be partly under voluntary control. This would mean that participants may choose to focus attention more at moments of high expectancy, while they might allow themselves to drift off task at low expectancy time points. If this is the case, it could be expected that mind wandering reports at moments of low temporal expectancy would be mostly characterized by *intentional* mind wandering. In contrast, if implicit temporal attention is a more automatic process, more *unintentional* mind wandering reports would be expected.

2. Experiment 1

2.1. Methods

2.1.1. Participants & procedure

Participants were thirty-seven healthy volunteers recruited though the internal website of the National University of Singapore (mean age [stdev] = 22.86 [3.19]; 19 females). All participants reported no history of psychiatric or neurological disorder, or long-term medication use, and had normal or corrected-to-normal vision.

As a part of a larger sleep-related protocol, participants came into the lab in the evening (7 pm) and stayed overnight. Upon entering the lab, participants signed informed consent, and performed one run of the Psychomotor Vigilance Task (PVT; Dinges & Powell, 1985), a sustained attention task that is sensitive to the effect of implicit timing, as well as being conducive for mind wandering (Unsworth & Robison, 2016, 2018). The first PVT run was performed without thought probes, to familiarize participants with its temporal distribution. Participants then received instructions about the thought probes. Every hour from 8 pm to 11 pm, they performed a PVT with thought probes (four runs). Afterwards, they stayed awake for the rest of the night performing hourly PVTs without thought probes, and in the morning they performed further attentional test. Only data from the four PVT runs including thought probes is reported here. It must be noted that these data were collected at time points at which vigilance performance is known to be comparable to normal daytime performance. Sleep related data will be reported elsewhere. All procedures were approved by the Institutional Review Board of the National University of Singapore.

2.1.2. Psychomotor Vigilance Task

Each PVT run started with the presentation of a fixation dot (see Fig. 1A). At random time intervals a target stimulus appeared (a running millisecond counter), to which the participant was instructed to respond as quickly as possible with a button press. Time intervals are randomly drawn from a uniform distribution (2–10 s; Fig. 2B). This temporal distribution makes target timing maximally unpredictable for each individual trial. However, implicit temporal expectations are formed through experience over multiple trials. In particular, the probability of target appearance increases with the passing of time. Accordingly, in this task attentional readiness (and faster RTs) is consistently found with longer foreperiod durations (Kong, Asplund, Ling, & Chee, 2015; Massar & Chee, 2015; Massar, Sasmita, Lim, & Chee, 2018; Matthews et al., 2017; Sasmita, Massar, Lim, & Chee, 2018; Tucker, Basner, Stern, & Rakitin, 2009; Yang et al., 2018). Typical reaction time patterns given the temporal distribution are illustrated in Fig. 2B.

To assess mind wandering, thought probes were inserted at quasi-random moments during the task (Fig. 2C). Participants were asked to characterize their mental state just prior to appearance of the thought probe, with response options: 1) On task, 2) intentionally mind wandering, and 3) unintentionally mind wandering. Following Seli, Risko, and Smilek (2016), participants were instructed that intentional mind wandering could be identified as instances in which “you intentionally decided to think about things that are unrelated to the task”, while unintentional mind wandering reflected moments when “your thoughts unintentionally drifted away to task-unrelated thoughts, despite your best intentions to focus on the task” (complete instructions can be found in the Supplementary material). Probe trials started identical to target trials - with the presentation of a fixation dot. After a random interval, the fixation dot was replaced with the thought probe (instead of a target stimulus). This ensured that, during the fixation period, participants did not know that a probe would be presented, and they would prepare in the same way as they would for an upcoming target stimulus. Critically, the time from fixation onset to probe onset (foreperiod) was controlled such that half of the probes had a short foreperiod (3–5 s), and the other half had a long foreperiod (7–9 s). This allowed us to examine whether mind wandering occurred more frequently at the early periods of the fixation interval (short foreperiod) compared to the later interval periods (long foreperiod). Eight thought probes were distributed equally across the 10-minute task runs, with one short foreperiod probe and one long foreperiod probe per 2.5 minute period. In total, four PVT runs with mind wandering probes runs were performed, amounting to a total of 16 probes per foreperiod duration. Each task run contained approximately 80 trials, resulting in a probe to target ratio of ~1/10.

2.1.3. Sample size justification

Power analysis based on recent studies from our lab using the same PVT task as the current study indicated that behavioral foreperiod effects are robust (partial-η^2: 0.705–0.817) (Massar et al., 2018; Sasmita et al., 2018), and a sample sizes of N = 6 to N = 8 would be sufficient to detect these effects with power = 90% and alpha = 0.05. However, no prior studies have examined the effect of foreperiod duration on mind wandering. For comparison, we estimated the necessary sample size based on known changes in mind wandering over the total duration of the PVT task (Time-on-Task effect). Reaction times in the PVT are known to deteriorate with Time-on-Task, with effect sizes being comparable to foreperiod-effects (Cohen's d = 0.88–1.06, Massar, Lim, Sasmita, & Chee, 2016; partial-eta squared = 0.60, Unsworth, Robison, & Miller, 2018).

Critically, frequency of mind wandering is also known to increase with time-on-task (Thomson, Seli, Besner, & Smilek, 2014), and a recent study using mind wandering probes in the PVT reported a linear increase with time-on-task, with effect size partial-eta squared = 0.32 (Unsworth & Robison, 2016). Power analysis indicated that a sample size of N = 26 would be necessary to detect this effect size with power = 90% and alpha = 0.05. As this was the most conservative estimate, we aimed to recruit at least 26 subjects. However, since the data collection was part of a larger protocol, we set out to collect as much data as the protocol would allow us to.

2.1.4. Analysis

As the task was performed in four separate PVT runs, data from all runs was combined for each participant. Following standard analysis practice for the PVT, responses faster than 150 ms were considered premature, and were omitted from analysis. All other RTs were binned based on Foreperiod (short foreperiod: 2 to < 6 s, long foreperiod: 6–10 s). Median RT was compared between foreperiod-bins using a paired-samples *t*-test. For thought probes, the proportion of all off-task responses was compared between foreperiod conditions using a paired t-test. Furthermore, to examine the separate contributions of voluntary and involuntary mind wandering, a repeated-measures ANOVA was performed with Foreperiod (short, long) and Intentionality (intentional, unintentional) as within-subject factors. Lastly, a correlation between foreperiod-effects in behavioral performance and in mind wandering was calculated.

For comparison, similar analyses were performed to examine Time-on-Task effects in RT and mind wandering. Median RT and proportion of off-task thought probe responses (irrespective of foreperiod duration)

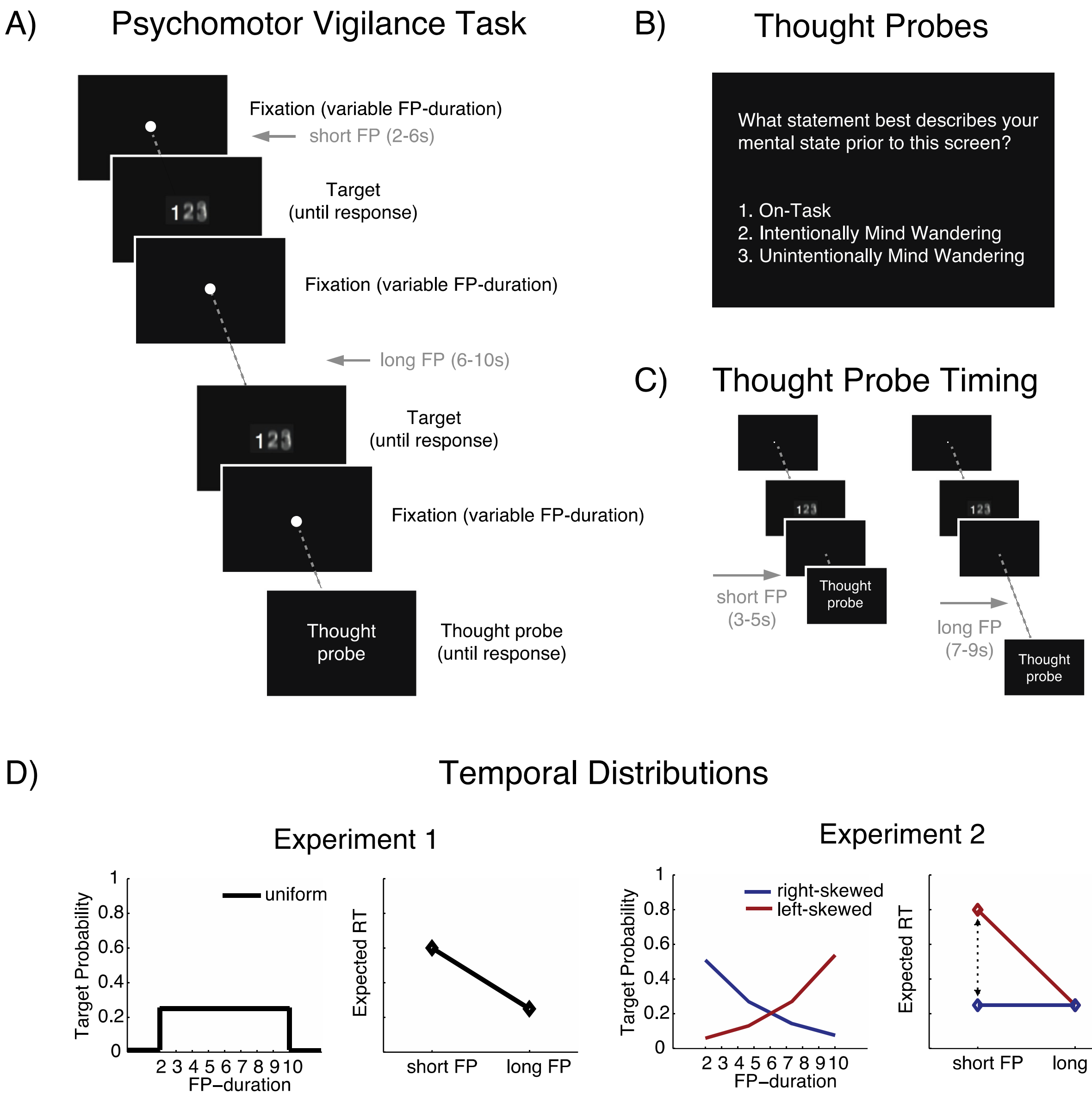

Fig. 1. A) Schematic of the task structure of the Psychomotor Vigilance Task. B) Example thought probe, presented at pseudo-random moments during the task. C) An equal number of probes was preceded by short foreperiods (3–5 s) or long foreperiods (7–9 s). D) Temporal distributions of foreperiod duration, and expected RT pattern in Experiment 1 (uniform distribution), and Experiment 2 (left vs right-skewed distribution). (FP = foreperiod.)

were quantified for four consecutive 2.5-minute time-on-task quartiles. Data were analyzed using repeated measures ANOVA's with time-on-task quartile (1, 2, 3, 4) as within-subjects factor. For all ANOVA analyses, Greenhouse-Geisser correction was performed when the assumption of sphericity was violated.

2.2. Results

2.2.1. Foreperiod effects

Attentional performance was significantly modulated by foreperiod duration, with slower RTs for short-foreperiod trials compared to long-foreperiod trials (see Fig. 2A; t(36) = 7.83, $p < .0001$, 95% CI = [13.92–23.65], Cohen's d_z = 1.29). As expected, RTs were slower for short-foreperiod trials (mean = 345.3, stdev = 31.11 ms) compared to long-foreperiods trials (mean = 326.6, stdev = 27.34 ms), indicating that attentional readiness grew with longer foreperiods. As it has been suggested that behavioral manifestation of mind wandering episodes should primarily be reflected in occasional long RTs (attentional lapses; Steinborn, Langner, Flehmig, & Huestegge, 2016), we further characterized the RT-distributions by fitting an ex-Gaussian model to the RT-distributions. This model is described by three parameters, a distribution mean (μ), variance (σ), and skewness (τ; describing the weight of occasional trials in the long right tail of the RT distribution). Paired *t*-tests demonstrated that short foreperiod trials were characterized by a higher mean RT (mean μ short = 293.63, stdev = 18.55; versus mean μ long = 285.62, stdev = 19.55; t(36) = 4.82, $p < .0001$), and a stronger skewness (mean τ short = 72.90, stdev = 34.14; versus mean τ long = 55.12, stdev = 31.30; t(36) = 4.93, $p < .0001$). No difference in distribution variance was found ($t < 1$, n.s.; see Fig. 2B for illustration of RT-distributions).

Unexpectedly, there was no difference in the proportion of off-task reports (mind wandering) to thought probes delivered after short foreperiods (mean = 0.37, stdev = 0.26), versus long foreperiods (mean = 0.37, stdev = 0.27; t(36) = 0.004, p = .997, 95% CI = [−0.054 0.054], Cohen's d_z = 0.00059). Looking closer at the different types of off-task responses, we performed a Foreperiod (short, long) × Intentionality (intentional, unintentional) repeated measures

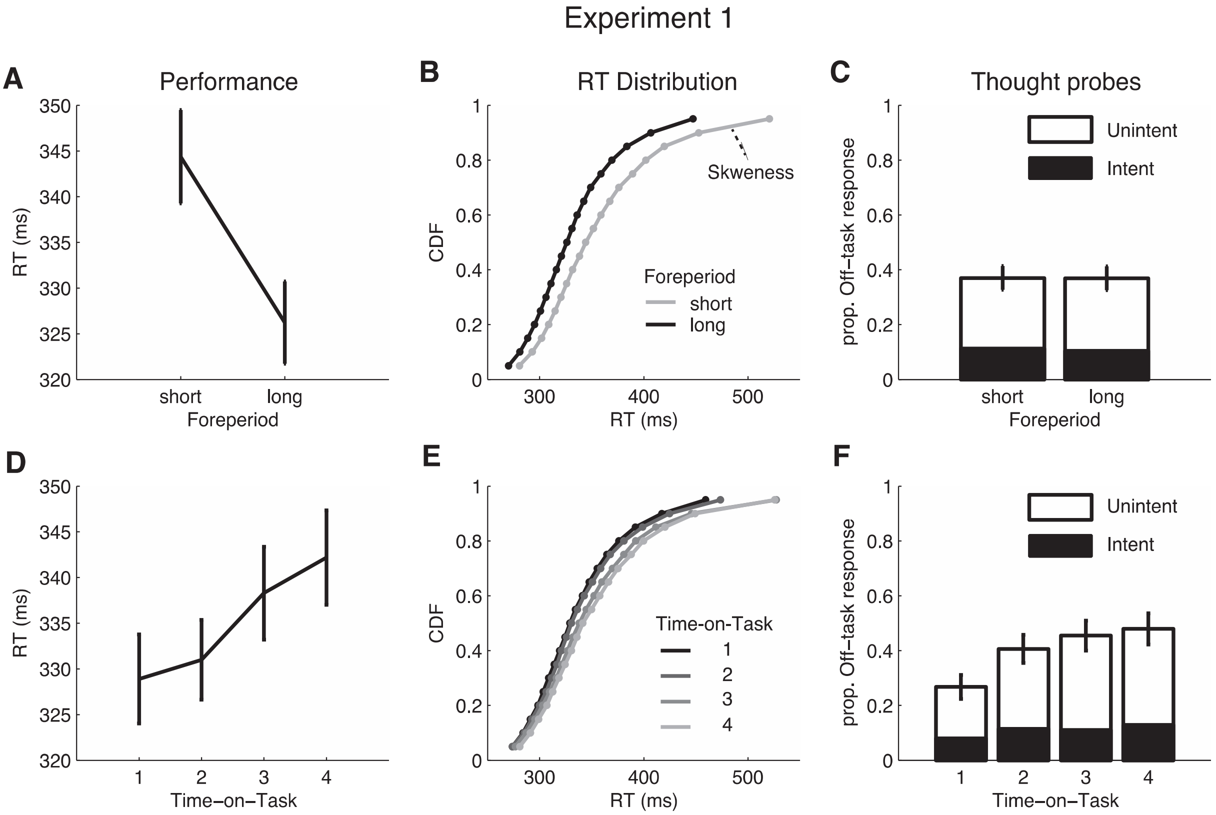

Fig. 2. Foreperiod effects (upper panels) and time-on-task effects (lower panels) from Experiment 1, with A & D) mean reaction times, B & E) cumulative distribution functions (CDF) for reaction times, and C & F) off-task response to thought probes.

ANOVA. This analysis showed that the majority of off-task reports were unintentional ($F(1,36) = 28.65$, $p < .0001$, partial-$\eta^2 = 0.443$). However, as in the main analysis, there was no main-effect or interaction with foreperiod (F's < 1).

2.2.2. *Time-on-Task effects*

To ensure that the absence of a foreperiod effect for mind wandering was not due to a lack of sensitivity of the thought-probe method, we examined whether off-task reports in our data changed as a function of time-on-task. With longer task performance, the frequency of mind wandering increases. 10-minute PVT runs were divided into four time-on-task bins (2.5 min/bin). As expected, RT and off-task reports increased with longer time-on-task (RT: $F(3,108) = 15.67$, $p < .0001$, partial-$\eta^2 = 0.303$; mind wandering: $F(3,108) = 13.16$, $p < .0001$, partial-$\eta^2 = 0.268$). The increase in mind wandering with time on task was dominated by unintentional mind wandering (Time-on-Task × Intentionality interaction: $F(3,108) = 3.57$, $p = .017$, partial-$\eta^2 = 0.090$).

Potentially, the association between mind wandering and attentional performance is only revealed at later time-on-task periods (Randall, Oswald, & Beier, 2014; Steinborn et al., 2016). To test for potential interaction effects a Foreperiod (short, long) × Time-on-Task (quartile 1, 2, 3, 4) was performed. Overall, results mirrored the findings from the main analyses. For RT, strong main effects for both Foreperiod ($F(1,36) = 72.28$, $p < .001$), and Time-on-Task ($F(3,108) = 12.51$, $p < .001$), but no interaction ($F(3,108) = 1.99$, $p = .12$). For mind wandering there was only a Time-on-Task main effect ($F(3,108) = 12.14$, $p < .001$), but no Foreperiod effect ($F(1,36) = 0.13$, $p = .72$), or interaction ($F(3,108) = 1.92$, $p = .13$).

Analysis of RT-distribution indicated that with increasing time-on-task RTs became significantly more skewed (mean τ quartile $1 = 52.81$, stdev $= 22.13$; versus mean τ quartile $4 = 73.37$, stdev $= 34.97$; $F(3,108) = 5.41$, $p = .002$; see Fig. 2E). No changes in distribution mean or variance were found (F's < 1).

2.3. *Sequential foreperiod effects*

It is known that foreperiod effects are further modulated by the immediate history of foreperiods experienced (sequential foreperiod effect). The effects of attentional readiness, i.e. faster RTs on a trial (n) with a long versus a short foreperiod, are more pronounced if the preceding trial (n-1) contained a long foreperiod. This is thought to reflect the statistical updating of temporal expectations, such that a long foreperiod on trial n-1 leads to an increased expectation of encountering a long again foreperiod on trial n. Consequently attentional readiness is lower (i.e. RT longer), when this expectation is violated (i.e. trial n = short foreperiod). Analyzing our data based on foreperiod length in the current (n) and preceding trial (n-1), indeed showed stronger foreperiod effects for trials preceded by long versus short foreperiods for behavioral performance (Fig. 3A; FPn × FPn-1 interaction: $F(1,36) = 42.91$, $p < .0001$). Mind wandering however (Fig. 3B) was neither sensitive to foreperiod length on the current trial, preceding trial or their interaction (all F's < 1.2, n.s.). This was true for intentional (all F's < 1.7, n.s.), and unintentional mind wandering responses (all F's < 1.2, n.s.).

2.4. *Discussion*

Results of Experiment 1 did not provide support for our hypothesis that mind wandering reports would be guided by foreperiod duration. Mind wandering was equally prevalent after short and long foreperiods. This was despite the fact that task performance was strongly dependent on foreperiod duration. Reaction times were significantly slower after short compared to long foreperiods, reflecting increasing attentional readiness based on implicit temporal expectations (Nobre et al., 2007). It therefore seems that the behavioral effects of implicit temporal

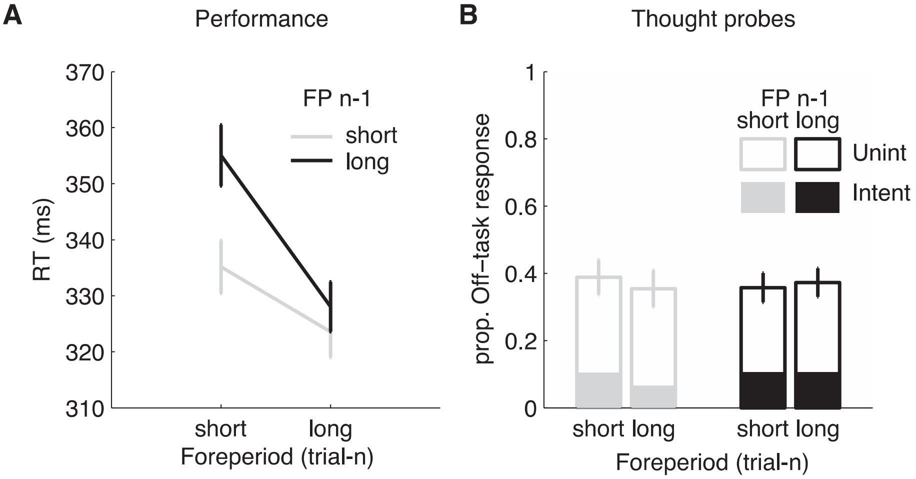

Fig. 3. Sequential foreperiod effects for, A) mean reaction times, and B) thought probe responses. FP = foreperiod, trial-n = current trial, n-1 = preceding trial.

expectation are not due to a higher occurrence of mind wandering at short foreperiods. This dissociation was further supported by the absence of a correlation between performance and thought probe effects. In contrast, the proportion of off-task reports increased over the duration of the 10-minute task (Time-on-Task effect). This indicates that the thought probe method was sufficiently sensitive to capture performance relevant changes in attention over time.

In light of these results, we sought to replicate and extend these findings in Experiment 2. In particular, we tested whether changing temporal expectations by altering the foreperiod distributions would influence the observed pattern of mind wandering episodes. Reaction times patterns are known to be strongly driven by the distribution of temporal events. We tested if mind wandering reports would follow these changes related to the temporal distribution of relevant events.

3. Experiment 2

As implicit expectations are formed by learning a particular temporal distribution of foreperiods (Los et al., 2001), attentional effects may be modulated by changing this distribution (Baumeister & Joubert, 1969; Trillenberg, Verleger, Wascher, Wauschkuhn, & Wessel, 2000). In a right-skewed distribution, where short foreperiods occur more frequently than long foreperiods, behavioral foreperiod effects are reduced (i.e. smaller differences between RTs for long and short-foreperiod trials), compared to a uniform distribution (see Fig. 1D). Conversely, in a left-skewed distribution, where long-foreperiod trials are more frequent, foreperiod effects are amplified (i.e. larger differences in RTs between long and short- foreperiod trials; Los, Kruijne, & Meeter, 2017; Mattiesing, Kruijne, Meeter, & Los, 2017). If the behavioral foreperiod effect is independent of mind wandering (as the results from Experiment 1 suggest), alterations in foreperiod distribution should change RT patterns in a predictable manner but should leave the pattern of off-task reports unchanged.

3.1. Methods

3.1.1. Participants & task

An independent sample of sixty-one participants was recruited (mean age [stdev] = 22.53 [2.94]; 39 females), all reporting no history of psychiatric or neurological disorder, or long-term medication use, and having normal or corrected-to-normal vision. Participants were recruited as part of a larger data collection and performed a battery of cognitive test for approximately 2 h. As part of this battery, they performed a 15-minute version of the PVT with thought probes included. Other tasks in the battery included a decision making task, a breath counting task, and a series of questionnaires. The PVT was performed as the second task in the battery after the decision making task. Here we report only the results from the PVT task.

The task was the same as the PVT from Experiment 1, with one notable difference: the distribution of foreperiods was not uniform, but either left-skewed or right-skewed (see Fig. 1B). Participants were randomly assigned to one of the two distribution conditions. In the right-skewed distribution (N = 31) targets were preceded by foreperiods ranging from 2 to 10 s with exponentially declining probability. This made that targets were more frequently presented after short foreperiods than after long foreperiods. In contrast, in the left-skewed distribution (N = 30) targets were more frequently preceded by long foreperiods compared to short foreperiods. As in Experiment 1, thought probes were inserted following either short foreperiods (3–5 s) or long foreperiods (7–9 s). A total of eight thought probes were inserted over a 15-minute task (with one short and one long-foreperiod probe inserted at random time points within each 3:45-minute Time-on-Task quartile). Primary analysis again focused on foreperiod effects in RT and thought probe responses, comparing both distribution conditions. Analysis for Time-on-Task effect was performed similarly as in Experiment 1.

3.2. Results

3.2.1. Foreperiod effects

For RT there was a significant main effect of foreperiod duration (see Fig. 4A; F(1,59) = 93.164, $p < .0001$, partial-η^2 = 0.612), and no main effect of distribution (F(1,59) = 0.965, p = .33, partial-η^2 = 0.016). As expected, there was a significant interaction between Foreperiod duration and Distribution (F(1,59) = 17.53, p = .0001, partial-η^2 = 0.229). Planned *t*-tests showed that the foreperiod effect was significant in both distributions (right-skewed: t(30) = 5.88, $p < .0001$, 95% CI = [13.31 27.49], Cohen's d_z = 1.06; left-skewed: t (29) = 7.72, $p < .0001$, 95% CI = [37.98 65.35], Cohen's d_z = 1.41), but was significantly less pronounced in the right-skewed compared to the left-skewed distribution (t(59) = −4.19, $p < .001$, 95% CI = [−46.20–16.32], Cohen's d = 1.07).

Analysis of ex-Gaussian parameters confirmed that mean RT-distribution (see Fig. 4B) was significantly longer in short versus long foreperiod trials in the left-skewed distribution (mean μ short = 320.20, stdev = 48.71; versus mean μ long = 280.90, stdev = 23.35), but not in the right-skewed distribution (mean μ short = 288.04, stdev = 27.37; versus mean μ long = 289.78, stdev = 35.92; Foreperiod × Distribution interaction: F (1,59) = 27.44, $p < .0001$). For τ, both Foreperiod distribution conditions showed an increase in long RTs on short compared to long foreperiod trials (F(1,59) = 4.52, p = .038), with no differences between distributions (Foreperiod × Distribution interaction: $F < 1$,

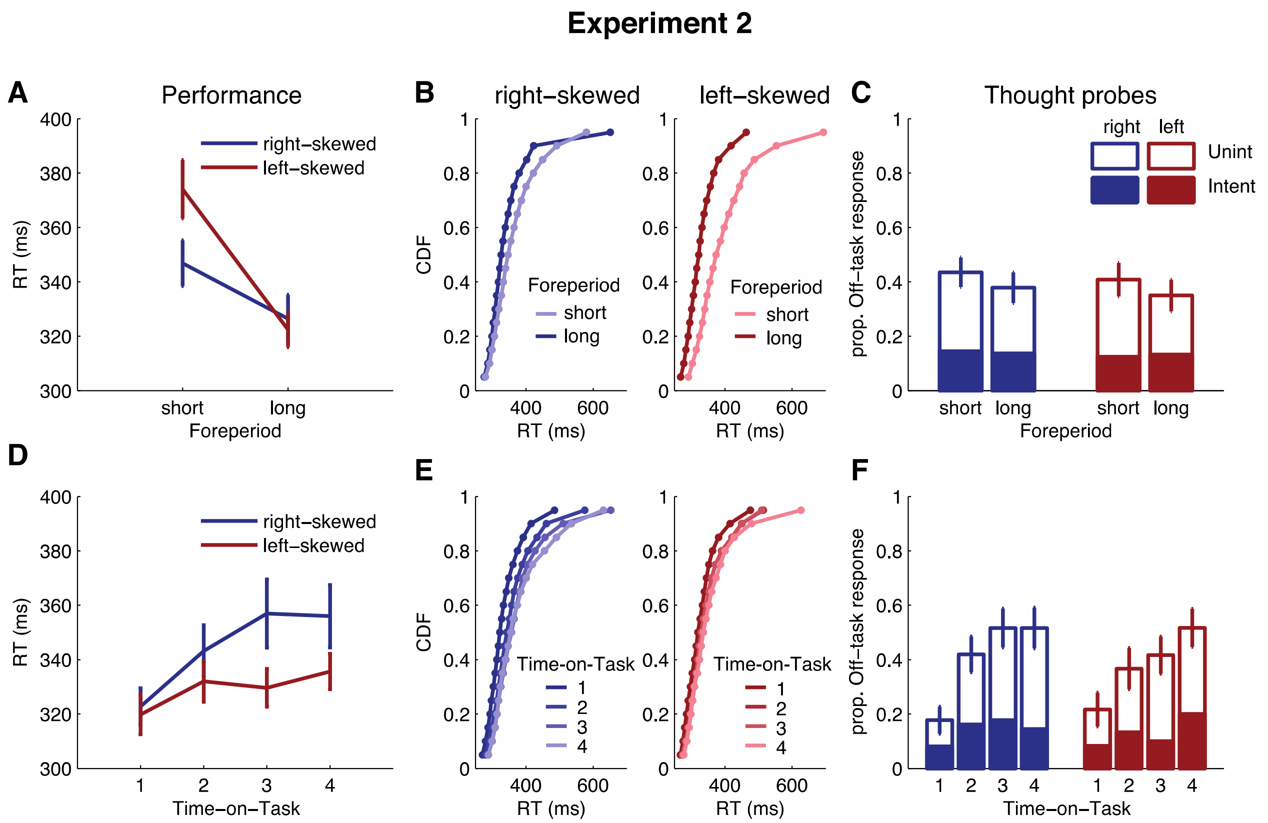

Fig. 4. Foreperiod effects (upper panels) and time-on-task effects (lower panels) from Experiment 2, with A & D) mean reaction times, B & E) cumulative distribution functions (CDF) for reaction times, and C & F) off-task response to thought probes, for right and left-skewed distribution.

n.s.). RT variability σ was not affected by Foreperiod (F(1,59) = 2.89, p = .094), Distribution (F(1,59) = 1.95, p = .168), or their interaction (F(1,59) = 0.198, p = .66).

As in Experiment 1, foreperiod duration did not influence off-task reports for thought probes (see Fig. 4C; F(1,59) = 1.96, p = .167, partial-η^2 = 0.032), neither was there a main-effect of distribution (F (1,59) = 0.16, p = .69, partial-η^2 = 0.003), nor a Foreperiod duration × Distribution interaction (F(1,59) = 0.00003, p = .98, partial-η^2 = 0.000009).

3.2.2. *Time-on-Task effects*

Comparing performance on the four time-on-task blocks yielded a significant main effect of time-on-task (see Fig. 4D; F(3,177) = 11.89, p < .0001, partial-η^2 = 0.366), but no main-effect of Distribution was found (F(1,59) = 1.87, p = .18, partial-η^2 = 0.031). Although the Time-on-Task effect seemed to be more pronounced in the right-skewed distribution compared to the left-skewed distribution the interaction between Time-on-Task and Distribution did not reach statistical significance (F(3,87) = 2.73, p = .059, partial-η^2 = 0.044). Separate analyses showed that the Time-on-Task effect was significant in both the right-skewed (F(3,90) = 8.26, p < .0001, partial-η^2 = 0.216), and the left-skewed distribution (F(3,87) = 4.57, p = .005, partial-η^2 = 0.136). Further, when quantifying the Time-on-Task effect as the difference between quartile 4 – quartile 1, no significant difference between the two distributions was found (t(59) = −1.64, p = .107, 95% CI = [−38.70 3.89], Cohen's *d* = 0.42).

Ex-Gaussian parameter analysis showed that the effects of Time-on-Task on RT were associated with an increase in RT-distribution mean μ (Time-on-Task main effect (F(3,177) = 4.05, p = .008; see Fig. 4E)), and an increase in RT-distribution skewness τ (Time-on-Task main effect (F(3,177) = 5.99, p = .001)), with no effects or interactions with foreperiod distribution (left-skewed versus right-skewed; all F's < 1.9). No changes in RT variance σ with Time-on-Task (all F's < 1).

For thought probes, there was a significant increase in off-task report with increasing Time-on-Task (see Fig. 4D; F(3,177) = 14.25, p < .0001, partial-η^2 = 0.194). There was no main-effect of Distribution (F(1,59) = 0.158, p = .692, partial-η^2 = 0.003), nor a Distribution × Time-on-Task interaction (F(3,177) = 0.664, p = .575, partial-η^2 = 0.011). Further dissection of thought probe responses into intentional and unintentional instances of mind wandering showed that a majority of off-task responses were unintentional, which increased with Time-on-Task (F(3,177) = 8.88, p < .0001, partial-η^2 = 0.131). No increase of intentional mind wandering was found with Time-on-Task (F(3,177) = 2.01, p = .114, partial-η^2 = 0.033).

To test for interaction effects between Foreperiod and Time-on-Task, a 3-way ANOVA was run. As in the main analysis, for RT there was a significant main effect of Time-on-Task (F(3,159) = 6.23, p = .003), Foreperiod (F(1,53) = 70.82, p < .001), and a Distribution × Foreperiod interaction (F(1,53) = 28.39, p < .001), but no further interactions (all F's < 1). For mind wandering there was only a significant effect of Time-on-Task (F(3,177) = 14.19, p < .001), with no significant effects or interactions for Foreperiod or Distribution (all F's < 1.6).

3.3. *Discussion*

Results from Experiment 2 show that a change in the temporal distribution of foreperiod durations can change behavioral foreperiod effects in a predictable manner. Participants in the left-skewed condition had a significantly stronger foreperiod effect than those in the right-skewed condition, in line with previous research (Los et al., 2017; Mattiesing et al., 2017). These results reflect that implicit temporal attention is driven by the specific shape of the foreperiod distribution. Despite these changes in behavioral foreperiod effects, thought probe responses did not differ in relation to foreperiod distribution. Under both distributions off-task reports were unrelated to foreperiod duration. Off-task reports were equally likely after a short foreperiod compared to a long foreperiod, replicating the results of Experiment 1. Again, off-task reports were mostly composed of unintentional mind wandering episodes, and off-tasks reports did increase with Time-on-Task, mirroring the performance decrement that was found for RT.

3.4. Combined analysis

To explore whether foreperiod and time-on-task effects in performance were proportional to mind wandering effects we conducted a correlational analysis combining data from both Experiments (N = 98). Individual foreperiod scores were calculated as the difference between short and long foreperiod trials for RTs and mind wandering responses. Time-on-task scores were calculated as the RT and mind wandering differences scores between quartile 4 and quartile 1. Bivariate correlations showed that foreperiod RT score and mind wandering were not correlated ($r = -0.010$, $p = .919$, 95% CI = [−0.208.189]). A positive correlation was found for increases in RT and mind wandering with time-on-task ($r = 0.448$, $p < .0001$, 95% CI = [0.274.593]). These findings further underline that the effects of implicit timing (but not time-on-task) are dissociable from mind wandering (see Supplementary materials for further details).

4. General discussion

The findings from Experiments 1 and 2 clearly show that behavioral performance in temporally unpredictable tasks is governed by implicit temporal expectations based on the passage of time given a learned temporal distribution. These data are in line with a wide literature on attentional readiness in variable foreperiod tasks. Contrary to our expectations, however, these behavioral effects were not paralleled by changes in mind wandering along foreperiod duration.

4.1. Mind wandering does not follow implicit timing

Our original hypothesis stemmed from findings that mind wandering can be modulated by temporal expectations in an explicit timing task, with predictable event timing (Seli, Carriere, et al., 2018). In the clock task of Seli, Carriere, et al. (2018), participants were fully aware of when a target event would occur. Mind wandering was found to be most frequent when target expectancy was lowest, i.e. when the clock hand was furthest away from the 12 h position. The PVT task in the current study is fundamentally different from this clock task, in that the passage of time is not marked by external cues, but needs to be monitored internally by the subject. Moreover, as target timing is variable, temporal predictions can only be formed implicitly, based on the passage of time and the experienced distribution. As such, it is less straightforward to determine the optimal timing for mental breaks, allowing the mind to drift away from a strict focus on task performance. Variable foreperiod tasks are therefore thought to be more mentally demanding, and less conducive to mind wandering (Langner & Eickhoff, 2013; Shaw et al., 2012; but see Unsworth & Robison, 2018 Experiment 3).

While task (dis)engagement cannot be explicitly timed in variable foreperiod tasks, there are clear effects of implicit timing in the form of the foreperiod effect (i.e. RT's are faster after long versus short foreperiods). These behavioral foreperiod effects were highly robust, with 34 out of 37 subjects showing the expected effect in Experiment 1, and 56 out of 61 subjects in Experiment 2. Yet, there was no such foreperiod effect for mind wandering reports, and RT effects were uncorrelated with mind wandering. Furthermore, altering the foreperiod distribution in Experiment 2 had clear and predictable effects on the behavioral foreperiod effect, but did not change the pattern of mind wandering along foreperiod duration. These findings suggest that the fluctuations in attentional performance due to implicit temporal expectations are independent of instances of mind wandering.

It is worth noting that previous studies that have used this task under predictable timing regimes (fixed ISI of 2 or 8 s), have found that participants report more mind wandering under the long ISI (8 s) condition than the short ISI condition (2 s: Unsworth & Robison, 2018, Exp 4). Furthermore, this effect of ISI duration was found to be more pronounced in individuals with low working memory capacity, and to emerge at later time-on-task blocks (Unsworth & Robison, 2020, Exp 3). This aligns with findings that mind wandering increases when targets are presented less frequently (McVay, Meier, Touron, & Kane, 2013; Smallwood et al., 2007), and indicates that mind wandering is sensitive to the temporal structure of the task. No prior studies however, have probed the occurrence of mind wandering at various moments during the foreperiod interval, which was essential to the current investigation.

4.2. Strategic versus automatic accounts of implicit timing

Mind wandering in the explicit timing task reflects strategic disengagement of attention from task performance, at moments when no critical events were expected (Seli, Carriere, et al., 2018). A benefit of this would be that cognitive resources could be dynamically reallocated to processes other than task performance, whenever task-focus is not strictly required (Thomson et al., 2015). In a similar fashion, strategic accounts of the foreperiod effect in implicit timing tasks have argued that establishing maximum attentional readiness is an active process that can only be maintained for short periods of time (Alegria & Delhaye-Rembaux, 1975). By monitoring the conditional probability, the observer can strategically direct attentional resources to the time points with highest target likelihood (Niemi & Näätänen, 1981). Accordingly, behavioral foreperiod effects are known to only emerge later in development (Vallesi & Shallice, 2007), and can be modulated by factors that alter strategic allocation of resources such as explicit expectations (Los & van den Heuvel, 2001) or motivation (Massar et al., 2018; Sasmita et al., 2018). Although the concepts of mind wandering, or on versus off-task focus, are not typically considered in strategic accounts of implicit temporal preparation, it could be argued that a strategic allocation of attention in time would correspond with stronger on-task focus. Conversely, it could be expected that moments in time at which attentional preparation is non-optimal, would be accompanied by higher mind wandering. The current data do not provide evidence for such a pattern.

Alternative views of implicit timing ascribe the observed fluctuations less to strategic preparation, but to a more automatic process of associative learning (trace conditioning; Los et al., 2001; Los et al., 2014). Attentional strength is conditioned on a trial-by-trial basis. Attention at moments that are paired with the presentation of a target are reinforced, leading to stronger attentional focus at these moments on subsequent trials. In contrast, moments that are bypassed are inhibited on later trials. In the situation of a uniform foreperiod distribution, all foreperiods are associated with an equal number of targets (i.e. they are reinforced equally often). However, given the fact that shorter foreperiods are bypassed more frequently, these foreperiods are inhibited more often, resulting in weaker associative strength (Los et al., 2014). While the conditioning account offers an elegant framework to understand foreperiod effects without invoking any strategic or intentional mechanisms, it does not explain why fluctuations in attentional strength over the foreperiod duration were not associated with fluctuations in mind wandering. Even if attentional readiness is purely governed by automatic associative learning processes, it could still be expected that moments of high attentional readiness would be marked by high on-task focus. It therefore remains to be elucidated how the mechanisms of implicit temporal preparation differ from those of off versus on-task attentional focus. Other mechanisms such as motor preparation (Carlsen & MacKinnon, 2010; Van der Lubbe, Los, Jaśkowski, & Verleger, 2004) or oculomotor stability (Amit, Abeles, Carrasco, & Yuval-Greenberg, 2019) may play a role, but it is clear from the current study that mind wandering does not contribute to the performance fluctuations under implicit temporal attention.

4.3. Mind wandering does follow time-on-task

In contrast to foreperiod effects, robust time-on-task effects were found for both reaction time and mind wandering. Performance deteriorated over the duration of the task, while instances of mind wandering became more frequent. These findings are in line with previous studies (Farley, Risko, & Kingstone, 2013; Krimsky, Forster, Llabre, & Jha, 2017; Randall et al., 2014; Thomson et al., 2014), and are thought to reflect reduced task focus and executive control due to fatigue (Helton & Warm, 2008; Kane et al., 2007) or due to volitional withdrawal of attentional resources (Kurzban et al., 2013; Massar et al., 2016; Thomson et al., 2015). Furthermore, the increase in reaction time and mind wandering over time were positively correlated, which supports the idea that they reflect related mechanisms.

Importantly, these findings demonstrate that the thought probe method was sufficiently sensitive to detect changes in mind wandering that were in the predicted direction and were behaviorally relevant. The lack of change in mind wandering due to foreperiod effects could therefore not simply be dismissed as a lack of sensitivity, but it could be taken as an indication that implicit timing and mind wandering are dissociable phenomena. It is relevant in this perspective that other studies have also demonstrated that the behavioral foreperiod effect and time-on-task effect are two independent phenomena, that influence performance separately, but do not interact (Langner, Steinborn, Chatterjee, Sturm, & Willmes, 2010).

4.4. Temporal dynamics of attention and mind wandering

Taken together, the results from the foreperiod and the time-on-task analyses paint a rich picture of the different temporal dynamics that influence attentional performance and mind wandering. While attentional performance, was reliably influenced by implicit temporal expectations, mind wandering was not. In contrast, attentional performance and mind wandering were both sensitive to longer task durations, with declining attentional performance and increasing mind wandering over time (indicating faltering task-focus with time-on-task), and were correlated across subjects (indicating associated processes). These findings demonstrate a clear dissociation whereby the temporal dynamics of attention fluctuations, are not mirrored by that of off-task cognition.

In the case of variable foreperiod effects, we found no evidence in support of mind wandering as an underlying reason for the observed lapses of attention at short foreperiods. These data however should not be taken to indicate that mind wandering only fluctuates at longer time scales (e.g. minutes of time-on-task versus second of foreperiod duration). As discussed earlier, fluctuations of attentional state are known to follow time-scales of second (e.g. 10–20 s, Bastian & Sackur, 2013). To date however, empirical research mapping out time courses of mind wandering is relatively scarce. On challenge in this endeavour is that subjective thought reports cannot be sampled at high frequencies (~1 probe/min). To infer fluctuations at a finer temporal resolution it is necessary to rely on behavioral (e.g. RT variability; Bastian & Sackur, 2013) or physiological (e.g. dynamic brain connectivity; Kucyi & Davis, 2014) correlates of mind wandering. To further unravel the temporal dynamics of mind wandering remains a relevant area of investigation. Our results contribute to this matter by outlining a specific area of temporal attention where mind wandering does not seem to hold pace with behavioral performance fluctuations (i.e. variable foreperiod effects).

4.5. Intentional versus unintentional mind wandering

Mind wandering in the present study mostly comprised unintentional mind wandering episodes (~26% unintentional versus ~10% intentional). This contrasts with the study by Seli et al. (2018) on explicit timing, where intentional mind wandering episodes occurred at equal or higher rates compare to unintentional mind wandering. With many other tasks, unintentional mind wandering episodes outweigh intentional mind wandering (Ju & Lien, 2018; Robison & Unsworth, 2018; Seli, Cheyne, Xu, Purdon, & Smilek, 2015). Intentional mind wandering may be more prevalent when the primary task is easy (Seli, Risko, & Smilek, 2016), or when participants are less motivated to perform the task (Robison & Unsworth, 2018; Seli et al., 2015). Unintentional mind wandering on the other hand, is correlated with individual differences in working memory capacity and arousal (Ju & Lien, 2018; Kane & McVay, 2012; Robison & Unsworth, 2018), and is more prevalent in slow-paced than fast-paced tasks (Unsworth & Robison, 2018). Our data further show that the increase in mind wandering with time-on-task was mostly composed of increases in unintentional mind wandering. Finally, as with overall mind wandering reports, there was no effect of foreperiod on intentional or unintentional mind wandering. Neither intentional nor unintentional mind wandering were changed in frequency after short or long foreperiods. This finding further underlines that the effects of foreperiod duration on implicit temporal attention are unrelated to mind wandering.

4.6. Limitations

Several limitations of the current study should be noted. First of all, the main result of this study is that we find no support for our hypothesis that mind wandering and implicit temporal attention (i.e. foreperiod effect) are related. Since this essentially represents a null-finding, it is important to remain cautious Several limitations of the current study should be noted. First of all, the main result of this study is that we find no support for our hypothesis that mind wandering and implicit temporal attention (i.e. foreperiod effect) are related. Since this essentially represents a null-finding, it is important to remain cautious when interpreting these data. Several aforementioned aspects of our investigation however help to inspire confidence in the reliability of our findings (i.e. time-on-task as a control analysis, dissociation between performance and mind wandering changes based on temporal distribution, or based on sequential foreperiod effects). In the end, we believe that we have thoroughly tested for the possibility that mind wandering and variable-foreperiod effects were related, but we have found no such evidence. In our view, these findings are informative of the temporal dynamics of mind wandering, and the dissociation between attentional fluctuations as measured with behavioral performance versus mind wandering. Admittedly, stronger conclusions could be drawn if our hypothesis was confirmed. We believe however that, in order to contribute to knowledge formation, and avoid bias, it is key to report null-results (on the condition that study methods are sufficiently robust; Ioannidis, Munafò, Fusar-Poli, Nosek, & David, 2014; Simonsohn, Nelson, & Simmons, 2014).

Another limitation is that the thought probes in the current study only included ‘on-task’, ‘intentionally mind wandering’ and ‘unintentionally mind wandering’ as response options. Prior research has identified other behaviorally relevant mental states that may not be clearly categorised under these labels (e.g. ‘external distraction’, ‘task-related interference’, Robison, Miller, & Unsworth, 2019; Stawarczyk, Majerus, Maj, Van der Linden, & D'Argembeau, 2011). Furthermore, within the category of mind wandering various different sub-categorizations have been proposed (e.g. ‘aware versus unaware’, ‘past-oriented versus future-oriented’; Miles, Karpinska, Lumsden, & Macrae, 2010; Schooler et al., 2011). The dimensionality and operationalisation of mind wandering is a matter of ongoing debate (for reviews see Christoff et al., 2018; Seli et al., 2018; Weinstein, 2017). It is possible that including more response categories into the current investigation would provide a richer view on various mental processes that influence attentional performance. Here, we focused on intentional versus unintentional mind wandering as this distinction holds relevance to the issue of strategic versus automatic attention allocation in temporal attention (Los, 2010). We found that in the PVT task, mind wandering episodes at short and long foreperiods were primarily unintentional. While our data do not allow us to say anything about the potential influence of mental states other than mind wandering, it does not take away from our main finding that mind wandering does not vary along fluctuations in implicit temporal attention.

It should further be noted that processes of implicit temporal attention have been studied through a variety of paradigms other than the variable foreperiod paradigm. Implicit temporal expectations can for instance also be formed by presenting stimuli following an isochronous rhythm (Sanabria, Capizzi, & Correa, 2011) or more complex recurring sequences (O'Reilly, McCarthy, Capizzi, & Nobre, 2008). In these cases, attention is found to be optimal when a target stimulus is presented in sync with the preceding rhythm or temporal sequence (O'Reilly et al., 2008; Sanabria et al., 2011). The formation of such temporal expectation is thought to be important in the perception of speech prosody and music, and may thereby be meaningfully related to the regulation of on-task attention and mind wandering. These forms of implicit temporal attention may rely on different cognitive and neural mechanisms than those involved in the variable foreperiod effect (for a review see Nobre & van Ede, 2018). It would therefore be interesting for future studies to examine the temporal dynamics of mind wandering in the context of rhythmic or sequential temporal regularities.

In a similar vein, it would be relevant to consider the effect of (temporal) regularities in other tasks that are commonly studied in relation to mind wandering. In the Sustained Attention to Response Task (SART), participants have to respond to a majority of trials, while withholding their response on rare target trials (Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). Having a majority non-target trials induces a pre-potent response tendency that needs to be inhibited whenever a target is detected. Manipulations of target frequency can lead to altered response strategies (e.g. fewer errors of commission), and shifts in mind wandering frequency (McVay et al., 2013; Smallwood et al., 2007). While such manipulations presumably change the dynamics of target expectancy, to our knowledge, no research has been done into the temporal aspects of this expectancy (i.e. would mind wandering frequency change with the sequence of target/non-target trials experienced).

5. Conclusion

In summary, we found mind wandering and implicit temporal attention as indexed by the magnitude of the foreperiod effect to be independent phenomena. The discrepancy between these findings and those from other timing tasks, suggests that implicit and explicit timing may involve different temporal mechanisms, which are dissociable from those influencing the propensity to mind wander.

Data & code availability

Data and code for this project are available through https://osf.io/w7bv8/.

CRediT authorship contribution statement

Stijn A.A. Massar: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Jia-Hou Poh:** Conceptualization, Methodology, Writing - review & editing. **Julian Lim:** Writing - review & editing, Supervision. **Michael W.L. Chee:** Writing - review & editing, Supervision, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2020.104242.

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