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*Original Research*

# Elevated Blink Rates Predict Mind Wandering: Dopaminergic Insights into Attention and Task Focus

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**Abstract**

**Background**: The study investigated the neural correlates of mind wandering using eyeblink rate (EBR) and variability (EBV) proxies. Dopamine, a neurotransmitter integral to the brain's reward system, has been implicated in regulating both task-unrelated and task-focused thinking. This study sought to clarify the relationships between dopaminergic function and cognitive control during a task by utilizing EBR and EBV as proxy measures. **Methods**:Vertical electrooculogram and brain event-related potential (ERP) data were gathered from 24 adult participants while they performed a computerized cognitive task. During the task (3-stimulus visual oddball procedure), participants discriminated between an infrequently seen target stimulus, an infrequent novel stimulus (for evaluating task engagement and distraction), and a commonly occurring nontarget stimulus. A retrospective questionnaire (Dundee Stress State Questionnaire, DSSQ) assessed task-unrelated (TUT) and task-related (TRT) thinking directly after task completion. The P3a ERP brain indexes at the Cz and Fz scalp electrode sites were also considered as a secondary proxy measure of dopamine function. **Results**: The main finding revealed that higher EBR was associated with higher TUT, suggesting a link between elevated dopaminergic activity and mind wandering. There was also a marginal negative correlation with P3a latency at the Fz scalp location and TUT, indicative of heightened responsiveness to distraction in general. For TRT, there was a positive correlation with P3a amplitudes at Fz, suggesting a role in task-related engagement and focus on all stimuli during the task. Regarding behavior, EBR and EBV were negatively correlated with Sigma ex-Gaussian task reaction time (RT), suggesting that more stable cognitive states are associated with higher blink rates and variability. Tau RT positively correlated with blink variability and P3a amplitudes at Fz and Cz, indicative of attentional lapse. Regression analyses showed that EBR and Mu RT predicted TUT, while TRT was predicted by P3a amplitude at Fz. More blinks and slower responses were related to TUT, whereas greater focus on the task stimuli (P3a amplitude) was related to TRT. **Conclusions**: These data underscore the importance of dopamine during mind wandering and task focus. In addition, this study argues for using ex-Gaussian analysis to understand the complex dynamics of attentional control during mind wandering.

**Keywords:** dopamine; eye blinks; mind wandering; attention; P300; event-related potentials; attentional control; cognitive flexibility; ex-gaussian

## 1. Introduction

Mind wandering, also known as stimulus-independent thinking, zoning out, mind pops, and task-unrelated thought (TUT), occurs when our brain shifts focus from the current task to unconnected ideas, reflections, and other musings [1]. This phenomenon is central to the human experience, enabling navigation between immediate sensory information and the internal world. This dynamic aspect of human cognition occupies up to 50% of our waking life [2] and profoundly affects everyday activities, impairing driving ability [3], reading comprehension [4] and academic performance [5]. Rumination, a specific type of mind wandering characterized by repetitive and negative thoughts, negatively impacts mental health [6]. Despite these drawbacks, mind wandering can enhance creative problem-solving [7], with some literature indicating that mind wandering episodes facilitate creativity and divergent thinking [8]. Historical anecdotes, such as Archimedes' bath, Newton's orchard, and Poincare's walk, illustrate its role in brilliant insights [9]. Additionally, mind wandering promotes positive self-reflection, emotional regulation [10], goal realization, and mental respite [11].

Mind wandering is challenging to define and measure, requiring sophisticated methodologies to dissect its elusive nature. Thought sampling and brain imaging techniques have shown that mind wandering is associated with activity in the default mode network (DMN) of cortical regions active during rest [12]. Behavioural approaches capture subjective experiences of TUT directly from participants through probe methods or retrospective questionnaires (see [13] for critical review). There is ongoing debate about the best method for assessing mind wandering, with retrospective questionnaires and probe methods each having limitations. Retrospective tools like the Dundee State Stress Questionnaire (DSSQ) allow precise distinction between task-related and task-unrelated thought without disrupting task performance, making them ideal for studies requiring continuous engagement. Neuroimaging methods like functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) reveal key DMN regions involved in TUT, including the medial prefrontal cortex, posterior cingulate cortex, and angular gyrus [14]. A meta-analytic review notes additional regions involved in spontaneous thought and suggests multiple distinct networks at work [15]. EEG has also demonstrated great promise in uncovering the mechanisms involved in the wandering mind. For instance, Barron and colleagues [16] conducted seminal research demonstrating how TUT dampens the processing of sensory information and distractor stimuli, supporting the decoupling hypothesis. This study utilized Event-Related Potentials (ERPs), such as the P3a component [17], to uncover how we switch from the external to the internal world, providing essential insights into the DMN's role in shifting focus. The current study employs this brain index along with eye blink metrics, as another crucial proxy measure of dopamine to examine the wandering mind.

Particularly relevant to our study goals, eyeblink rate (EBR) has been widely accepted as a biological marker of central dopamine ([18] for review). Central dopamine levels regulate blinking by influencing the striatum and its pathways, ensuring blink efficiency and promoting good eye health. Additionally, central dopamine influences the brain's reward system, where positive or negative stimuli or thoughts can elicit dopamine release, indirectly modulating blink rate. For example, Riby and colleagues [19] measured spontaneous eye blinks as a proxy measure of dopamine release in response to classical music, finding that blink rate significantly increased with music associated with strong emotional tones. It is worthwhile to highlight that both positive and negative content may produce this effect. In a related field, ocular observations of dopamine (DA), as well as dopaminergic dysregulation, have been fundamental to understanding patient groups. For instance, investigations of schizophrenic participants have shown that these individuals often exhibit increased blink rates, suggesting heightened striatal dopamine activity [20]. Conversely, patients with Parkinson's disease, characterized by dopamine deficiency, typically display reduced blink rates [21]. These examples extend the relevance of EBR across various neuropsychiatric and neurological conditions, demonstrating its utility as a research tool. Beyond this, the consistent and reliable correlations between DA and EBR underscore the intricate connection between DA, EBR, and cognitive processing. This connection not only justifies the utility of EBR as a measure of DA but stresses the importance of exploring the role of dopamine in both external and internally driven trains of thought. Thus, using blink rate and variability as proxy measures provides a valuable tool in investigating the wandering mind, offering insights that are difficult to capture through other means.

Neuro-cognitive accounts suggest that ocular measures can be effectively used to disentangle the processes involved in TUT. For instance, Nakano and colleagues [22] demonstrated that participants' blinks while watching a film were linked to momentary activation of the DMN. When the film was intermittently blacked out at a rate and duration that matched blink rates, this DMN activation was absent, suggesting that blinking may actively engage attentional disengagement and trigger TUT states. The authors suggest that eyeblinks control the disengagement of attention by momentarily deactivating the dorsal attention network while activating the DMN. Ueda and colleagues [23] expanded this research by investigating blinks and cognitive processes during creative tasks where mind wandering is crucial to success. Participants' blinks increased when engaged in divergent thinking tasks such as generating novel uses for objects where introspection is required to explore multiple solutions. This does not occur for converging thinking, where sustained focus on the internal environment is often a requirement. This research underscores the potential of ocular measures as sophisticated signals of the brain's internal and external demand management, providing a promising avenue for exploring the neurological foundations of mind wandering and its relation to dopaminergic activity. Additionally, Huette *et al*. [24] described blinks as an under-utilized resource for measuring task engagement, emphasizing the need for further investigation. Their research indicated that blink rates vary with task demands, suggesting that they can serve as reliable indicators of cognitive load and engagement. Elsewhere, other ocular measures have been championed in the study of the wandering mind, such as in the study of pupil size and eye gaze [25]. These studies on ocular physiology underscore the need for proxy measures to infer psychological functioning that is otherwise difficult to measure.

To deepen our understanding of the relationship between blinks, dopamine, and mind wandering during task performance, this study also incorporates ex-Gaussian analysis of reaction times (RTs), further elucidating attention dynamics during periods of mind wandering. Parris *et al*. [26] have highlighted how Mu, Sigma, and Tau can reveal underlying attentional processes that might be overlooked using traditional RT measures, emphasizing their utility in understanding task engagement and attentional lapse. This statistical approach decomposes RT distributions during a task into three components: Mu (the mean of the Gaussian component), Sigma (the standard deviation of the Gaussian component), and Tau (the exponential component). Importantly, each of these components reflects different aspects of attentional processes. Mu indicates the general speed of processing and is related to cognitive control. Sigma captures the variability in response times, providing insight into attentional stability and consistency. Critically, Tau reflects the impact of occasional lapses in attention, indicating moments of disengagement or cognitive failures often associated with TUT. By analyzing these parameters, we aim to gain comprehensive insights into the multifaceted nature of attention during task performance. Recent studies have effectively used ex-Gaussian analysis to dissect cognitive processes, including Stroop tasks, demonstrating its robustness in capturing the multifaceted nature of attention and cognitive control (e.g., [27]). This approach is warranted in our investigation as it helps interpret the main findings related to blinks and task performance. To our knowledge, the novel use of ex-Gaussian analysis has not been previously applied to disentangle the attentional dynamics of mind wandering.

The present study explores the neural correlates of mind wandering and cognitive control by examining the relationships between dopaminergic activity indexed by eyeblink rate (EBR) and also blink variability (EBV) and task performance. We also use the P3a ERP component as another measure of dopamine, which has been utilized in our larger body of work as a confirmatory dopamine index [16]. Specifically, this research focuses on how these dopamine-related measures relate to TUT and task-related thought (TRT). Higher EBR and greater EBV are hypothesized to be associated with increased TUT. This is based on two key mechanisms: first, elevated blink rates and variability reflect increased dopaminergic activity, which is associated with greater cognitive flexibility and a propensity for mind wandering. Second, more mind wandering, instead of focusing on the present activity, likely involves emotionally laden thoughts, which are known to engage the dopaminergic system. To be clear, the first mechanism reflects dopamine's role in shifting attention, while the second highlights its role in processing the emotional content during mind wandering. Conversely, lower EBR and less EBV are associated with higher levels of TRT, indicating more stable cognitive states and greater task engagement, reflecting more focused attention and cognitive control. Additionally, the study will analyze ex-Gaussian RT parameters (Mu, Sigma, Tau) in relation to cognitive performance. Mu, representing the central tendency of reaction times, is predicted to be higher with increased TUT, suggesting longer average reaction times are linked to cognitive disengagement. Sigma, reflecting RT variability, is expected to be lower, indicating more stable cognitive states and engagement during episodes of TRT. Tau, capturing RT distribution skewness and lapses in attention, is predicted to positively correlate with TUT and negatively correlate with TRT. Finally, P3a ERP measures, indicating enhanced cognitive control and engagement with the task will be examined. It is predicted that there will be a positive correlation between P3a amplitudes and TRT and a negative correlation between P3a amplitudes and TUT. By integrating physiological monitoring of eye blinks, brain ERPs, and cognitive task performance with retrospective questionnaire data, this study aims to comprehensively understand the cognitive and neural mechanisms underlying mind wandering and cognitive engagement.

## 2. Materials and Methods

*2.1 Participants*

Twenty-seven adults participated in this study. Further details and a description of the first part of this program of work can be found in [16]. Participants were recruited via email and verbal invitations, which included a brief description of the study's requirements. All participants provided written consent. Ethical approval was obtained from the Department of Psychology Ethics Board at Northumbria University. During the analysis phase, three datasets were excluded due to incomplete data caused by excessive electrode noise. Consequently, the final sample comprised twenty-four participants (Mean age = 21.1 years, SD = 4.2).

*2.2 Measures*

2.2.1 The 3-Stimulus Oddball Task

The 3-Stimulus Oddball task has been extensively used to measure neurocognitive aspects of attentional and task engagement during EEG studies [17]. The paradigm was presented to participants using E-Prime Software (version 2.0, Psychology Software Tools, Pittsburgh, PA, USA) on a 17 ½-in monitor. Participants were instructed to use the spacebar on a standard keyboard in response to the target stimulus, and to ignore all other stimuli that appeared. The stimuli were characterized as the following: The target stimulus (Red Circle, area = 12.6 $cm^2$), the standard stimulus (Green Square, area = 16 $cm^2$) and the novel stimulus (Blue Square, area = 256 $cm^2$) appeared on 13%, 74%, and 13% of trials respectively. Following a 10-trial practice block, participants completed the testing phase, which consisted of 4 blocks of 50 trials. Each stimulus stayed on the screen for 100 ms, with inter-stimulus interval lasting from 830 ms–930 ms. A simplified summary of the task procedure is provided in Fig. 1.

2.2.2 The Dundee-State-Stress Questionnaire

At the end of the cognitive testing session, participants completed the thinking component of the DSSQ which measures transient states associated with performance-related stress [28]. The 16-item questionnaire was divided into two, eight-item factors to establish two components of the participants' meta-cognitive experiences during the task: TUT and TRT. Participants were asked about how often they thought about something unrelated to the task at hand (TUT), as well as how often they thought about something related specifically to the task such as performance (TRT). Examples of TUT and TRT questions were "I thought about something that happened earlier today" and "I thought about how I should work more carefully" respectively. Questions were answered using a 5-point Likert

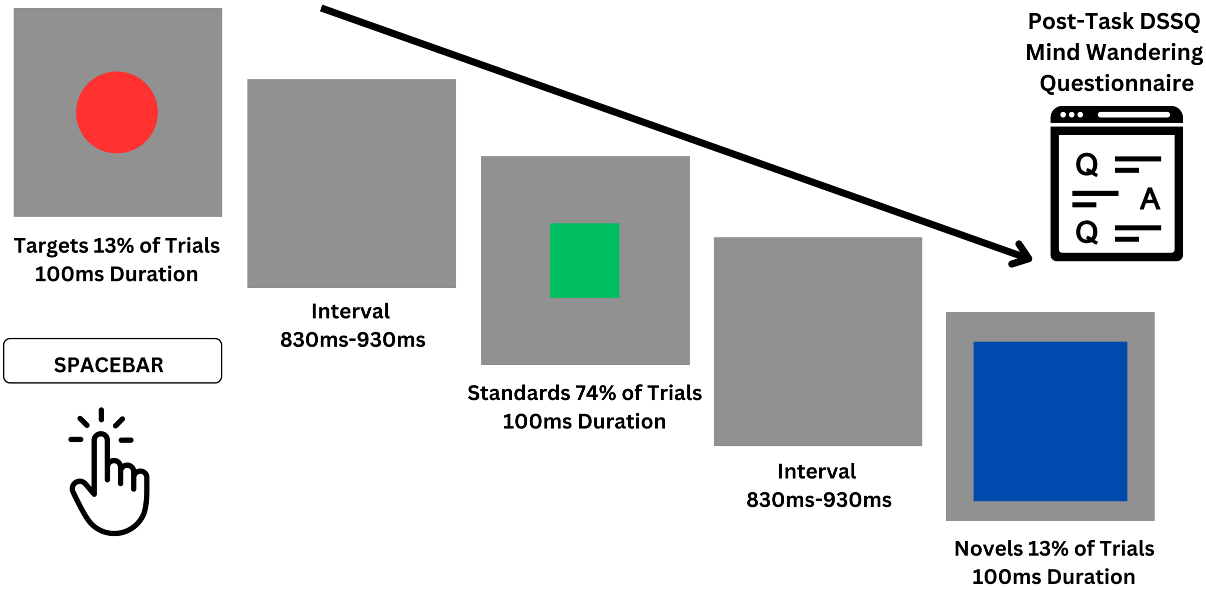


**Fig. 1. Task design: 3-stimulus oddball paradigm with post-task Dundee Stress State Questionnaire (DSSQ).**

scale (never = 1, once = 2, a few times = 3, often = 4, very often = 5). Answers were subsequently collated to build a mind wandering profile for each participant, whereby higher scores indicated high levels of TUT during the three-stimulus oddball paradigm.

2.2.3 Eye Blinks

Vertical electrooculogram was recorded to EBR and EBV, this was done by placing electrodes above and below the left eye. Researchers identifying the blinks were trained on the characteristics of ocular EEG data, including duration, attributes, and tempo prior to the study taking place, such that they recorded a correct and valid assessment. As each data collection session took approximately the same time, EBV was assessed using six, 150-second intervals in each dataset to determine average variability in blink rate, starting from when the oddball task commenced.

2.2.4 Event-Related Potentials

An electrode cap (BioSemi B.V., Amsterdam, Noord-Holland, Netherlands) with 32 channels of EEG recordings were employed to measure ERP's. Electrode placement was selected using the international 10–20 system [29], involving 4 midline sites (Fz, Cz, Pz, Oz), 14 sites over the left hemisphere (FP1, AF3, F3, F7, FC1, FC5, C3, T7, CP1, CP5, P3, P7, PO3, O1), and 14 sites over the right hemisphere (FP2, AF4, F4, F8, FC2, FC6, C4, T8, CP2, CP6, P4, P8, PO4, O2), and were subsequently referenced to the linked mastoid process. Signals were digitized at a rate of 2048 Hz, with a recording epoch of 1200 ms. Automatic eye blink correction, artifact rejection (values outside the range –75 uV to +75 uV), and averaging were carried out offline using Neuroscan EDIT 4.3 software (Compumedics, El Paso, TX, USA). The Fz and Cz electrodes were used to capture the P3a ERP component.

*2.3 Procedure*

Participants attended the laboratory, were briefed on the aims of the research, as well as what they would be expected to do, and were asked to provide written consent. All participants were attached with an electrode cap and electrodes on the bottom and top of their left eye. They proceeded to complete the 3-Stimulus Oddball Paradigm, followed by the Thinking Component of the DSSQ immediately after. Participants were subsequently debriefed and thanked for their participation.

## 3. Results

*3.1 Analytical Strategy and Statistical Analysis*

All data were analyzed using SPSS Software (version 29, IBM Corp., Chicago, IL, USA), with RStudio (Version Build 764, RStudio PBC, Boston, MA, USA, https://www.r-project.org/) used specifically for ex-Gaussian transformations. We started by calculating descriptive statistics for all variables: EBR, EBV, TUT, TRT, and P3a brain measures (Latency and Amplitude at FZ and CZ locations). Both FZ and CZ were considered in the initial correlations, but only FZ was used in the regression analyses due to potential collinearity issues (see [17] for a discussion of the locations where the P3 ERP components are centered). To ensure the RT data was suitable for subsequent analyses, we transformed it using the ex-Gaussian method. This transformation normalizes the RT data, providing a comprehensive characterization of the distribution by generating parameters for the mean (Mu), variability (Sigma), and skewness (Tau). The "retimes" package in R Studio was used to calculate the three components of the ex-Gaussian distribution. The ex-Gaussian model was fitted to the data using the "mexgauss" function, providing estimates for the

**Table 1. Pearson's correlations between thought focus (TUT & TRT), blink proxy measures (EBR & EBV), P3a event-related potentials (amplitude & latency) and ex-Gaussian reaction times (Mu, Sigma and Tau).**

| | DSSQ_TRT | DSSQ_TUT | Blink rate | Blink variability | P3aAmp_FZ | P3aAmp_CZ | P3aLat_FZ | P3aLat_Cz | Mu | Sigma | Tau |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DSSQ_TRT | 1 | | | | | | | | | | |
| DSSQ_TUT | 0.20 | 1 | | | | | | | | | |
| Blink rate | –0.03 | 0.58** | 1 | | | | | | | | |
| Blink variability | –0.03 | –0.02 | 0.47* | 1 | | | | | | | |
| P3aAmp_FZ | 0.44* | –0.15 | –0.35 | –0.01 | 1 | | | | | | |
| P3aAmp_CZ | 0.39 | –0.18 | –0.20 | –0.04 | 0.90*** | 1 | | | | | |
| P3aLat_FZ | 0.07 | –0.39# | –0.24 | 0.11 | –0.15 | –0.26 | 1 | | | | |
| P3aLat_Cz | 0.12 | –0.25 | –0.16 | 0.23 | 0.02 | –0.09 | 0.72*** | 1 | | | |
| Mu | 0.21 | 0.22 | –0.19 | –0.29 | –0.22 | –0.33 | 0.18 | 0.17 | 1 | | |
| Sigma | –0.22 | –0.07 | –0.48* | –0.66*** | –0.06 | –0.07 | –0.05 | –0.04 | 0.39 | 1 | |
| Tau | 0.13 | –0.25 | 0.03 | 0.41* | 0.50* | 0.41* | 0.14 | 0.09 | –0.4 | –0.53*** | 1 |

Note: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, #$p = 0.058$. TUT, task-unrelated thought; TRT, task-related thought; EBR, eyeblink rate; EBV, eyeblink variability; DSSQ, Dundee Stress State Questionnaire; Amp, amplitudes; Mu, mean.

mean, standard deviation, and exponential parameters. Initial Pearson's correlation analyses explored relationships between EBR, EBV, TUT, TRT, P3a ERPs and the ex-Gaussian RT parameters. This identified general patterns before targeted regression analyses. We conducted stepwise regression analyses to pinpoint predictors for TUT and TRT, mapping to our research questions and hypotheses. Specifically, TUT and TRT will be the dependent variables, with EBR, EBV, and P3a measures (Latency and Amplitude at FZ), and ex-Gaussian parameters as predictors.

### *3.2 Bivariate Correlations*

Pearson's bivariate correlations were computed to assess the relationship between all variables as can be seen in Table 1.

Given the large set of potential predictors in Table 1, stepwise regression was used to select variables for inclusion in the final models. This approach allowed for the identification of the most relevant predictors for TUT and TRT while minimizing model complexity and addressing potential multicollinearity.

### *3.3 TUT Regression*

A stepwise regression analysis was conducted to predict Task-Unrelated Thoughts. The eye blink rate and the Mu component of RT were extracted and contributed to the models. The first model, which included only EBR, was significant, $F(1,22) = 11.409$, $p = 0.003$, and explained 34.1% of the variance in TUT scores. The inclusion of the Mu component in the second model significantly improved the model, $F(2,21) = 8.810$, $p = 0.002$, explaining 45.6% of the variance. The coefficients for the final model were as follows: EBR ($\beta = 0.651$, $p < 0.001$), and Mu ($\beta = 0.345$, $p < 0.05$). This suggests that higher EBR and higher Mu values are significant predictors of increased TUT scores.

### *3.4 TRT Regression*

A stepwise regression analysis was conducted to predict Task-Related Thoughts. Only the P3a amplitude at the Fz electrode contributed to the model. The model was significant, $F(1,22) = 5.190$, $p = 0.033$, explaining 19.1% of the variance in TRT scores. The coefficient for P3a amplitude at Fz was significant ($\beta = 0.437$, $p = 0.033$), indicating that higher P3a amplitude at Fz significantly predicts increased TRT scores.

### *3.5 Post Hoc Power Analysis*

G*Power was used to calculate post hoc power for the abovementioned data. The correlation between EBR and TUT was $r = 0.472$, with a post hoc power of 78% ($n = 24$). Similarly, the correlation between P3a amplitude at Fz and TRT was $r = 0.437$, with a power of 71% ($n = 24$). In the regression analysis predicting TUT from EBR and Mu there was 89% power. Finally, predicting TRT from P3a amplitude there was 62% power.

## 4. Discussion

Despite the inherent challenges in measuring mind wandering, studying this phenomenon is crucial for understanding the dynamics of attentional control processes. The primary aim of the current work was to examine the relationship between the dopamine-proxy measures (EBR and EBV) and mind wandering, as indexed by TUT and TRT. TUT refers to instances where attention drifts from the task to unrelated internal thoughts or external stimuli. These thoughts often involve personal reflections and everyday distractions [30]. On the other hand, TRT refers to thoughts directly relevant to the task, focusing on performance, strategies, or stimuli within the task environment. The results demonstrated a strong link between elevated EBR and increased TUT, potentially reflecting heightened dopaminergic activity during mind-wandering episodes. This finding alone aligns with the comprehensive review by [18], which highlighted EBR as a reliable predictor of individual differences in dopamine-related cognitive performance. This finding supports two accounts linking dopamine function and the wandering mind, with previous research indicating that dopamine is crucial in cognitive flexibility and emotional processing [10]. Considering TRT and incorporating a more sophisticated analysis of behaviour affords an additional level of analysis, helping to interpret the complex interplay between attention, cognitive engagement, and mind wandering.

The observed association between elevated EBR and increased TUT in the present study supports two key mechanisms that associate dopamine function with the wandering mind. First, mind wandering is often rich in emotional content. Research indicates that a significant portion of mind wandering episodes involves thoughts related to personal goals, past experiences, and future plans, many of which are emotionally charged [1]. This emotional engagement can trigger dopamine release due to the involvement of the brain's reward system in processing emotionally significant stimuli. The dopaminergic response influences blink rate, likely through its modulation of the basal ganglia, which can affect the spinal trigeminal complex, a component suggested to be part of the blink generator circuit [31]. Thus, the frequent engagement of emotionally laden thoughts during mind wandering could explain the increased EBR, reinforcing the utility of blinks as a proxy for dopamine activity.

The second mechanism relates to cognitive flexibility and its role in human cognition. Indeed, cognitive flexibility is critical for managing the shift between external tasks and internal thoughts. Dopamine's role in cognitive flexibility facilitates the mental shifts in attention required for mind wandering, allowing individuals to disengage from the immediate environment and engage in introspection [32]. This flexibility is essential for the fluid transition between task-related focus and task-unrelated thoughts, underpinning the cognitive processes involved in mind wandering. The positive correlation between EBR and TUT may reflect this enhanced cognitive flexibility, supported by dopamine's regulatory function. Dopamine not only supports cognitive flexibility but is also vital for working memory [33], as it helps maintain and manipulate information within the prefrontal cortex, ensuring both stability and adaptability [34]. The stepwise regression analysis revealed that EBR and Mu, a marker of cognitive control, significantly predicted TUT, suggesting that heightened dopaminergic activity (indicated by higher EBR) and slower, less consistent reaction times (indicated by higher Mu) contributed to increased mind wandering. The specific contributions of behavioural components are discussed in detail below. Conversely, the negative correlation between P3a latency and TUT indicates that shorter latencies are associated with more mind wandering. Faster brain responses may reflect greater cognitive flexibility but also suggest less sustained attention, aligning with the idea that increased distractibility contributes to higher TUT.

Task-related thoughts and reflections represent focused, task-specific thinking and indicate cognitive engagement and sustained attention. These processes are fundamental to efficient functioning and goal achievement in simple and complex activities, ensuring our actions are purposeful and aligned with our objectives (e.g., [35]). Our study revealed a positive correlation between P3a amplitude at the Fz electrode site and TRT. The P3a findings suggest that individuals with higher P3a amplitudes not only maintain better attention to task-relevant stimuli but also exhibit heightened sensitivity and responsiveness to all stimuli in their environment. The enhanced attentional orientation supports more comprehensive cognitive engagement, allowing for better detection and processing of both expected and unexpected events. Importantly, increased P3a amplitude does not necessarily indicate a negative outcome. Riby and colleagues [36] noted that higher P3a amplitudes can reflect an increase in cognitive resources allocated to processing both relevant and irrelevant stimuli without impairing task-relevant processing. This shows that heightened P3a brain responses can represent more effective cognitive engagement rather than a deficit. The P3a component emerged as a significant predictor of TRT in our targeted regression analysis, confirming the importance of processing both task-related and unrelated stimuli during task completion. Our suggestion that the P3a can also be used as a proxy measure of dopamine and attentional control is warranted, given what we know about neurotransmitter activity associated with the P3 generation. Indeed, the dual-transmitter hypothesis suggests that P3a frontal-attention processing is associated with dopaminergic activity and is consistent with anatomical work [17], and with the assessment of the P3a in Parkinson's patients [37].

By supporting cognitive control processes that allocate and maintain attention on relevant stimuli, dopamine enables individuals to stay engaged with the task at hand, highlighting its importance in sustaining task-related focus and enhancing overall cognitive performance [38]. The distinct findings for P3a latency and amplitude reflect their differing functional roles. P3a latency, which relates to the speed of attentional shifts, is linked to TUT because slower response times indicated increased mind wandering. In contrast, P3a amplitude, which reflects the allocation of attentional resources, is associated with TRT, as heightened engagement with all stimuli supports sustained task focus.

The ex-Gaussian analysis provided crucial insights into the neuro-cognitive mechanisms underlying TUT and TRT. By decomposing RT distributions into Mu, Sigma, and Tau, we explored how these components reflect distinct aspects of attention. Regression analysis confirmed Mu as a significant predictor of TUT, highlighting dopamine's role in sustaining cognitive control during tasks, as suggested by Braun and colleagues [33]. Sigma, reflecting the variability in RTs, was negatively correlated with EBR and EBV, suggesting that more stable cognitive states, associated with higher blink rates and variability, are linked to lower RT variability. This implies that individuals with less variable reaction times may maintain more consistent focus and attentional control. Importantly, Tau, which captures the slowest and most extreme RTs associated with attentional lapses, was positively correlated with blink variability and P3a amplitudes at both Fz and Cz electrode sites. This indicates that attentional lapses, as reflected in the longer reaction times, are linked to variability in blink patterns and enhanced neural responses to unexpected distractor stimuli. The ex-Gaussian parameters highlighted different facets of attentional processes that traditional RT measures might obscure, making it particularly valuable for studying the multifaceted nature of mind wandering, dopamine and its impact on task performance [26].

The implications of our work extend to refining contemporary models of mind wandering by integrating physiological measures like EBR and EBV with cognitive and behavioural data. The joint consideration of behaviour and electrophysiological measures should be noted especially when examining difficult-to-measure psychological phenomena like mind wandering. Doing so gives us a more holistic understanding of the complex interplay between dopamine, attention, and mind wandering. Our findings support the use of blink rates as non-invasive proxies for dopaminergic activity, offering a practical tool for cognitive neuroscience research. However, it's crucial to acknowledge that EBR and EBV, while valuable, are influenced by multiple factors beyond dopamine alone, which could limit their specificity but provide utility when imaging methods are less accessible to the neuroscientist. Thus, future research should aim to further validate these measures across diverse contexts and populations, ensuring their robustness and reliability. The absence of an effect for EBV may reflect its role in capturing transient fluctuations in attention, while EBR is more closely linked to overall dopaminergic activity and stable cognitive states, making it a stronger predictor of mind wandering. It is also worthwhile noting that retrospective TUT and TRT probing provided useful insights into task-related thought processes. However, future research would benefit from a dedicated resting baseline to better clarify task-induced changes and enhance interpretability. In addition, although retrospective methods like the DSSQ rely on participants' recall and meta-cognitive awareness, they offer precision in distinguishing between task-related and task-unrelated thought without disrupting task performance. Future studies could explore whether the patterns observed in this study are consistent when using probe methods, providing further validation of the findings. Regardless of the abovementioned limitations, the novelty of this study lies in its integrative approach, combining behavioural, physiological, and neural measures to model distinct aspects of task-related and task-unrelated thought. In addition, the inclusion of ex-Gaussian parameters alongside blink metrics and ERP components provides new insights into the mechanisms underpinning attentional control, mind wandering and task engagement.

## 5. Conclusions

In conclusion, our study highlights the intricate relationship between dopamine, mind wandering, and task engagement, emphasizing the need for multifaceted approaches to effectively capture difficult-to-measure complex cognitive phenomena using a range of self-reported and neurological techniques. The integration of ex-Gaussian analysis provided a deeper understanding of how different aspects of attention, such as cognitive control, stability, and lapses, contribute to the experience of mind wandering and its impact on task performance.

## Availability of Data and Materials

Data are available at the Northumbria University Research Repository, https://figshare.northumbria.ac.uk/.

## Author Contributions

All authors (LR, LM, LB-M, JG, CH, DM, and JS) contributed to the conceptualization and methodology of the study. Data analysis was conducted by LR, LM, and CH. The original draft was written by LR and LM, while all authors reviewed and edited the final draft. LR supervised the project and, along with LM, undertook project administration. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

## Ethics Approval and Consent to Participate

The study received full ethical approval from the Department of Psychology Ethics Board at Northumbria University (Submission Ref. 737) and was carried out in accordance with the guidelines of the Declaration of Helsinki. All participants or their families/legal guardians gave written consent.


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## Conflict of Interest

The authors declare no conflict of interest. Leigh M. Riby is serving as one of the Editorial Board members of this journal. We declare that Leigh M. Riby had no involvement in the peer review of this article and has no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to Bettina Platt.

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