The Temporal Dynamics of Mind-Wandering and Meta-Awareness

by

Taren Rohovit

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Dissertation Committee:
Ulrich Mayr, Chair
Brice Kuhl, Core Member
David Unsworth, Core Member
Melissa Redford, Institutional Representative

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DISSERTATION ABSTRACT

Taren Rohovit

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Title: The Temporal Dynamics of Mind-Wandering and Meta-Awareness

Mind-wandering is a common feature of everyday life, yet most research has treated it as a relatively static contrast between being on task and being off task. This has made it difficult to study one of its most basic properties: that mind-wandering unfolds over time. In this dissertation, I address that gap by developing a new method to estimate when mind-wandering begins, and then use that method to examine the temporal dynamics of mind-wandering across behavioral, individual-difference, and neural levels of analysis. First, I introduce a novel audiobook-based paradigm that uses self-reports of the last remembered text to approximate mind-wandering onset, and I validate this approach with eye-tracking. Next, I use this method in a large individual-differences study to test competing models of how on-task and mind-wandering episodes relate to one another over time. Finally, I examine the neural correlates of mind-wandering across time using EEG, with particular focus on the onset, maintenance, and end of self-caught mind-wandering episodes. Across these studies, the results indicate that mind-wandering has meaningful temporal structure at more than one scale, that on-task and mind-wandering episode durations are best understood as reflecting separable underlying processes, and that the transition into meta-awareness begins before participants explicitly report catching themselves mind-wandering. Together, these findings argue for a more temporally structured account of mind-wandering than is typical in the current literature.

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CHAPTER I

INTRODUCTION

During everyday tasks such as reading a book, or driving, you may occasionally notice that your attention unintentionally drifts away from the task at hand, towards an internal narrative that exists independent of your current situation. For example, while intending to be working, you might start to think about an upcoming trip, or even something as routine as what you're going to make for dinner. This is the phenomena of mind-wandering; defined more pointedly as a shift of attention away from the external world towards internal, stimulus-independent, thought (Schooler et al., 2011). Despite our best effort to remain on task during everyday life, mind-wandering is an extremely prevalent experience with some studies estimating 30-50% of our waking life being spent mind-wandering (Killingsworth & Gilbert, 2010; Kane et al., 2007).

As one can imagine, spending this much time in an internally distracted state is not without consequence, during mind-wandering performance on the current intended task typically declines as fewer attentional resources are available (Mooneyham & Schooler, 2013; Smallwood et al., 2007). The cost of mind-wandering can also extend beyond performance metrics. Specifically, Ruminating on unwanted thoughts--a type of mind-wandering--is a major component of depressive and anxious disorders (Carriere et al., 2008; Killingsworth & Gilbert, 2010; Nayda & Takarangi, 2021; Watkins, 2008). The prevalence, and seemingly high cost of mind-wandering has motivated a relatively large body of research aiming to understand the

cognitive and neural mechanisms that give rise to mind-wandering, and the conditions under which it becomes potentially maladaptive.

Current Models of Mind-Wandering

Perceptual Decoupling Hypothesis

A core theoretical framework for understanding mind-wandering is the Perceptual Decoupling Hypothesis, which proposes that when attention shifts inward, perceptual processing of external stimuli declines (Smallwood, 2013). Mind-wandering reflects a reallocation of cognitive and perceptual resources away from sensory input and toward internally generated thought. The Perceptual Decoupling Hypothesis suggests that this may serve an adaptive purpose; by reducing interference from the external environment, the mind can sustain complex internal trains of thought such as planning, reflection, or problem-solving. Consistent with this idea, task performance is predicted to decline on tasks during periods of mind-wandering because the executive systems supporting task performance are effectively disengaged from the task and instead occupied by internal thought.

Empirical support comes from converging behavioral and neuroimaging studies. Behaviorally, participants exhibit slower reaction times and reduced perceptual sensitivity immediately before reports of mind-wandering (Kam et al., 2011; Smallwood et al., 2008). Neurally, such episodes are characterized by reduced sensory-evoked responses and increased activity in the default mode network, a set of regions argued to be associated with internally oriented thought (Christoff et al., 2009; Fox et al., 2015; Kam et al., 2011).

Executive Failure Hypothesis

The Executive Failure Hypothesis by contrast, posits that off-task thoughts arise when cognitive control fails to maintain current task goals (McVay & Kane, 2010). Here, mind-

wandering reflects a breakdown in sustained attention. When executive resources are insufficient or overtaxed, task irrelevant thoughts are able to intrude, and mind-wandering ensues. Unlike the Perceptual Decoupling Hypothesis, the Executive Failure Hypothesis treats mind-wandering as a largely passive process, and assumes that mind-wandering episodes do not require the same cognitive control resources that on-task focus does.

Evidence for the Executive Failure Hypothesis comes from both individual differences and experimental studies. Individuals with higher working memory capacity generally experience less frequent mind-wandering, though this finding is somewhat task-dependent (Kane et al., 2007; McVay & Kane, 2010; Robison & Unsworth, 2015). Dual-task or high-cognitive-load conditions that strain executive resources reliably increase mind-wandering (McVay & Kane, 2012). Neuroimaging studies further support this breakdown in executive control, showing that mind-wandering episodes are associated with reduced activity in control networks, such as the dorsolateral prefrontal cortex and anterior cingulate cortex, and increased activity in the default mode network, consistent with a shift away from goal-directed processing—though as described later, this finding is somewhat dependent on whether a probe-caught or self-caught mind-wandering detection method was used (Christoff et al., 2009; Fox et al., 2015; Kucyi et al., 2013). Overall, while this hypothesis explains why mind-wandering occurs, it treats mind-wandering episodes primarily as unintended failures, without addressing the timing, duration, or regulation of mind-wandering episodes.

Resource Control Hypothesis

The Resource Control Hypothesis builds on the Perceptual Decoupling Hypothesis and the Executive Failure Hypothesis, attempting to reconcile the two into a single framework (Thomson et al., 2014, 2015). The Executive Failure Hypothesis explains off-task thought mainly

as a breakdown in cognitive control, and the Perceptual Decoupling Hypothesis emphasizes an inward shift of attention that requires some amount of executive control resources to maintain (McVay & Kane, 2010 Smallwood & Schooler, 2006; Schooler et al., 2011). The Resource Control Hypothesis in comparison, proposes that mind-wandering emerges from the dynamic competition between task-focused and internally directed attention for a limited pool of executive resources (Thomson et al., 2014, 2015). In this framework, in line with the Perceptual Decoupling Hypothesis, mind-wandering itself actively engages control resources, rather than occurring solely as a result of executive failure. Importantly though, because both mind-wandering and on-task states draw from a limited pool of executive resources, control failures characteristic of the Executive Control Hypothesis can also be explained. The Resource Control Hypothesis thus reconciles the two other accounts, it explains the inward focus described by the Perceptual Decoupling Hypothesis, while also predicting lapses in task performance that resemble the effects highlighted by the Executive Failure Hypothesis. Mind-wandering is therefore not simply a breakdown of control, nor merely a shift inward, it reflects a continuous, resource-dependent competition between internal and external attention.

Explicit tests of this hypothesis remain limited, but several studies provide indirect support for a competition for control resources between on-task and mind-wandering states. Behaviorally, performance on response-inhibition and working-memory updating tasks declines during mind-wandering (even under conditions where baseline task demands could easily be met) indicating that these executive functions are actively engaged elsewhere, likely in a mind-wandering related process (Smallwood et al., 2008; Kam et al., 2011). Computational modeling further shows that mind-wandering is associated with reduced ability to inhibit habitual responses and diminished attention to rare, but task-critical events, again suggesting that

cognitive control resources are being consumed by internal thought rather than simply remaining idle (van Vugt & Broers, 2022). Neurally, mind-wandering appears to recruit not only default mode network regions but also control-related areas such as rostrolateral PFC and dACC, suggesting that mind-wandering does indeed in some way consume executive resources (Christoff et al., 2009; Fox et al., 2015; Kucyi et al., 2013).

Current Models of Meta-Awareness

Meta-awareness is the ability to explicitly notice where one's attention is currently being directed (Schooler et al., 2011). In the context of mind-wandering, meta-awareness refers to the moment that one becomes aware that attention has drifted away from the current task at hand. Once this realization has occurred, attention can be reoriented back towards the task. In comparison to mind-wandering research, work specifically on what causes this seemingly spontaneous meta-aware state is in its infancy. Nevertheless, several mechanistic accounts have begun to specify what triggers meta-awareness and how it operates.

A theoretical line of work situates meta-awareness within a monitoring framework: a supervisory process intermittently assesses whether focus aligns with one's current goals. When an incongruency is detected, meta-awareness enables one to notice their off-task states and potentially reorient attention back to the task at hand (Schooler, 2002; Seli et al., 2017). Building on this idea, a more detailed emerging approach conceptualizes meta-awareness within a hierarchical monitoring framework (Fleming & Daw, 2017; Sandved-Smith et al., 2021). In this view, the mind constantly generates predictions not only about the external world but also about its own internal states. Meta-awareness occurs when higher-level monitoring systems evaluate these internal signals and infer, with enough confidence, that attention has drifted from

the task. Once this "awareness threshold" is crossed, the cognitive system updates its internal model of where attention is being directed and can trigger corrective control processes (meta-awareness) that re-engage attention with the task. In this sense, meta-awareness is not a continuous background process but a discrete event, an internally generated "realization" that attention has lapsed. Research specifically on the processes that underlie meta-awareness are scarce, but the studies that do exist suggest that motivation, value-based signals, and mindfulness differences can modulate meta-awareness, consistent with this theoretical control-monitoring framework (Zedelius et al., 2015).

Methods to Measure Mind-Wandering

Probe-Caught

One consistent challenge mind-wandering research has faced is measurement. Mind-wandering is a covert shift of attention away from the environment, towards internal, stimulus independent, thought. Further, although some mind-wandering is deliberate, much of mind-wandering is spontaneous, and unintentional, meaning that individuals themselves typically don't even notice when mind-wandering begins. Nevertheless, researchers have found methods to measure differences between on-task, and mind-wandering states.

The most widely used approach to measuring mind-wandering is the experience sampling or probe-caught method (Smallwood & Schooler, 2006). Here, participants perform an ongoing task, such as reading, or sustained attention, while intermittently being interrupted by thought probes. When a probe occurs, participants report where their attention was immediately prior to the probe (either being on-task or mind-wandering). In the case of measuring some kind of dependent variable between on-task and mind-wandering conditions, the researcher will

typically select some temporal interval, for example 5 seconds, prior to a mind-wandering-reported-probe to classify as mind-wandering. This method is popular because a) it can be implemented into almost any task b) it allows the researcher to control the amount of data being collected, allowing for the frequency of mind-wandering to be estimated and c) because probes ask about the direction prior to the probe itself, these probes don't contaminate task data, allowing for the possibility of EEG and fMRI experiments. For all these reasons, the probe-caught methods remain the most popular approach for categorizing data into periods of on-task focus, and mind-wandering.

However, probe-caught methods also have several limitations. Perhaps most notable, because probes ask about only the current direction of one's attention, this method precludes the ability to measure duration, or onset time of a mind-wandering episode (Smallwood, 2013). Moreover, because probes interrupt participants, the probe itself may alter the natural dynamics of mind-wandering by increasing meta-awareness (Schooler et al., 2011). Finally, probe frequency involves a trade-off: high probe rates yield finer temporal resolution but risk disrupting task engagement, while sparse probing improves ecological validity at the cost of temporal precision. Despite these challenges, probe-caught experience sampling remains the most common method for studying mind-wandering and has provided many of the core insights into its prevalence, individual differences, and neural basis.

Self-caught

In contrast to probe-caught approaches, self-caught methods rely on participants to self-report instances of mind-wandering whenever they themselves notice that their attention has drifted. When participants realize that they are no longer focused on the task, they are instructed to press a button or otherwise signal that they have "caught" themselves mind-wandering

(Schooler et al., 2011). This method involves making use of participants' meta-awareness of their own attentional state, making it particularly useful for investigating the processes that bring mind-wandering to an end and thus provide a unique window into the transition between mind-wandering and re-engagement with a task.

The main advantage, and disadvantage of the self-caught method is that it necessarily requires the involvement of meta-awareness. For researchers wanting to understand how mind-wandering naturally unfolds and ends, this self-caught paradigm is ideal. However, because detection of these episodes requires meta-awareness, mind-wandering episodes that end without awareness are not reported and missed. Further, the degree to which one is aware of their own mental states likely depend on some degree of individual differences adding an additional complication to this method (Nayda & Takarangi, 2021; Ibaceta & Madrid, 2021; Seli et al., 2015). Overall, the self-caught method is less popular than the probe caught because of these additional considerations, but this method remains a staple for research that is specifically interested in the end point of mind-wandering.

Probe-Caught vs. Self-Caught

Probe- and self-caught methods generally produce broadly consistent findings. A study examining rates of mind-wandering during classroom lectures directly compared the two approaches and found that both methods capture similar rates of mind-wandering (Varao-Sousa & Kingstone, 2019). However, other work argues that probe-caught approaches should capture more episodes since probe-caught reports often capture episodes of which the participant was unaware, whereas self-caught reports require the return of awareness which could be underreported (Schooler et al., 2004). Both probe-caught and self-caught methods also show similar neural signatures. For instance, neuroimaging and electrophysiological comparisons

show that both recruit the default mode network; although, there is some evidence that self-caught episodes may additionally engage frontoparietal control regions associated with monitoring and reorienting attention (Christoff et al., 2009; Golchert et al., 2017; Liu et al., 2021).

Overall, the literature directly comparing probe-caught to self-caught methods is relatively sparse, but the studies that do exist show that probe- and self-caught methods yield broadly similar findings. The key differences that do emerge appear to reflect where in the mind-wandering episode measurement occurs, and whether mind-wandering occurred with or without awareness. Probe-caught reports typically capture the mind in the midst of an episode, often before awareness has returned, whereas self-caught reports occur near the end of an episode, when meta-awareness has occurred, and attention is being reoriented toward the task.

Other Behavioral Mind-Wandering Detection Methods

Beyond self-report methods, researchers have also used other behavioral metrics to infer mind-wandering from patterns of task performance. One of the most consistent findings is that periods of mind-wandering are accompanied by greater variability in reaction times; when attention drifts, reaction times become less consistent, leading to both unusually fast and unusually slow reaction times (Bastian & Sackur, 2013; Smallwood et al., 2004; McVay & Kane, 2012). Another common behavioral signature is an increase in commission and omission errors particularly in sustained attention tasks such as the Sustained Attention to Response Task (SART) (Cheyne et al., 2009; Robertson et al., 1997; Smallwood et al., 2004). Similarly, other recent work shows that mind-wandering reduces the efficiency of inhibitory triggering in stop-signal tasks (Jana & Aron, 2022).

These methods all have the unique advantage of being online measures of task focus and can thus estimate the onset and duration of mind-wandering. However, these methods are highly task specific, requiring the use of a task where reaction times, and/or error rates are relevant. Additionally, reaction time and error rates are indirect measures of mind-wandering, meaning that changes in performance must be inferred to reflect shifts in attention from on-task to mind-wandering. This limitation should be particularly salient at transition points between on-task and mind-wandering where smooth changes in behavior may cause incorrect estimations of mind-wandering onset time.

Eye-Tracking

Beyond behavioral measures, eye-tracking is another widely used approach to infer mind-wandering from continuous, online data. Metrics such as fixation duration, saccadic amplitude, and pupil diameter have all been shown to differ between on-task and mind-wandering states (Faber et al., 2020; Uzzaman & Joordens, 2011; Pelagatti et al., 2018). However, while eye-tracking has been highly successful in capturing these changes, findings are not always consistent. For example, some studies report increased pupil diameter during mind-wandering, whereas others observe decreases, depending on task demands, arousal, or the type of internally focused thought (Unsworth & Robison, 2018; Pelagatti et al., 2018). Similarly, saccadic amplitude and fixation patterns can vary across tasks, and the magnitude and direction of effects are sometimes inconsistent even within a single paradigm (Faber et al., 2020; Uzzaman & Joordens, 2011).

Some recent studies have attempted to detect mind-wandering directly from eye metrics using machine learning or predictive modeling approaches, with modest success (Faber et al., 2020; Pelagatti et al., 2018). However, these efforts face clear limitations: eye-tracking remains

an indirect measure, and it may fail to capture complex or nonlinear dynamics of mind-wandering episodes. For example, the drift into mind-wandering may display completely independent patterns in eye-data than the maintenance of mind-wandering. Without a direct measure of mind-wandering onset, these approaches are likely to miss this "drift into" stage, and only correctly categorize maintenance stages which can more reliably be categorized with experience sampling methods. These nuances highlight that eye-metrics are powerful tools for studying mind-wandering, but interpretations must carefully consider task context, and perhaps most importantly the dynamics of mind-wandering.

Electroencephalogram (EEG)

EEG has also been widely used to detect neural differences between on-task and mind-wandering states. Across paradigms, mind-wandering is associated with increased low-frequency power, particularly in the theta and alpha bands, though the exact topography and direction of alpha effects vary across tasks (Arnau et al. 2020; Baldwin et al. 2017; Compton et al., 2019; Rodriguez-Larios & Alaerts, 2021). A recent systematic review concluded that increased alpha activity is the most reliable spectral signature of mind-wandering states, accompanied by reduced sensory ERPs (P1, N1, and P3) reflecting disengagement from external input (Kam et al., 2022).

Given these strong EEG findings, several studies have attempted to use machine-learning classifiers trained on features such as theta and alpha power, and ERP amplitudes to distinguish on-task from mind-wandering states with moderate to high success rates (Dong et al., 2021; Hosseini & Guo, 2019; Jin et al., 2019). However, without a reliable non-neural measure of mind-wandering onset, it is currently unknown if these EEG classifiers are able to detect the entire duration of mind-wandering episodes, as opposed to just being able to detect the

occurrence of a mind-wandering episode. Consequently, although these approaches are clearly valuable, they may be limited in precisely identifying the *onset* time of mind-wandering.

Limitations of Current Methods

Overall, a variety of methods have been developed to measure mind-wandering, including probe-caught and self-caught paradigms, behavioral metrics, eye-tracking, and EEG. Each approach has offered unique contributions to the literature on mind-wandering, yet all share a common limitation: without a reliable measure of when mind-wandering begins, it is difficult to determine the full temporal dynamics of an individual mind-wandering episode.

Overview of the Dissertation

Mind-wandering is not a static mental state, but a process that unfolds over time. In everyday life and in the laboratory, individuals alternate between periods of on-task focus and mind-wandering, yet most existing research has treated mind-wandering as a discrete state measured at isolated moments. As a result, relatively little is known about the temporal structure of mind-wandering: when episodes begin, how long they last, how they are maintained, and how they end through meta-awareness. The goal of this dissertation is to characterize these temporal dynamics by examining the full cycle of mind-wandering, including the duration of on-task focus, the drift into and maintenance of mind-wandering, and the processes that precede the moment of meta-awareness.

Across three studies, I develop and validate a novel paradigm for estimating the onset time of mind-wandering episodes (Chapter 2, Experiment 1), use this paradigm to test competing models of how on-task and mind-wandering durations are related (Chapter 2, experiment 2), and

examine continuous EEG dynamics across the mind-wandering cycle (Chapter 3). Chapter 2, Experiment 1 introduces and validates a novel experimental paradigm for identifying the onset of mind-wandering in real time. Participants listen to an audiobook and report whenever they realize they have been mind-wandering. By indicating the last segment of the audio they remember before their attention drifted, participants provide a behavioral estimate of when the episode began. Eye-tracking data are used to validate this onset estimate, revealing systematic changes in eye behavior across the beginning, middle, and end of each episode. Using segmented multilevel regression, I demonstrate that eye-movement patterns evolve dynamically across these phases, with distinct signatures near episode onset.

Chapter 2, Experiment 2 employes this new paradigm to test three candidate models of mind-wandering temporal dynamics: (1) a single-process model, in which one underlying mechanism governs both on-task and mind-wandering durations; (2) an independent-process model, in which each state arises from its own, independent process; and (3) an opponent-process model, in which on-task and mind-wandering states "compete" for some shared resource. Data from a large individual-differences study are used to evaluate these models at both an individual difference level using structural equation modeling and a within-individual difference level using a lag-structured analysis. Individual difference measures of working memory capacity, ADHD symptoms, and trait mindfulness are incorporated to examine whether these traits predict differences in on-task versus mind-wandering durations. Across these analyses, on-task and mind-wandering durations were best characterized as two independent processes. This finding suggests that the mechanisms that allow someone to remain on task are not likely to be the same mechanisms that determine how long mind-wandering episodes persist.

Chapter 3 examines how oscillatory brain activity reflects transitions between on-task focus, mind-wandering, and meta-awareness. Using EEG data collected with the same paradigm, I examine how spectral power in alpha and theta bands changes across the onset, maintenance, and ending of mind-wandering episodes. Alpha activity is used to characterize changes in internally versus externally oriented attention across the episode, whereas theta activity is used to test whether control-related processes emerge near the moment of meta-awareness. The results show that alpha increased as participants entered and maintained mind-wandering, but began to decline several seconds before self-report, suggesting that the attentional state associated with mind-wandering started to shift before participants explicitly noticed the lapse. Theta showed a different temporal profile, with a later pre-report effect closer to meta-awareness. This pattern suggests that the end of mind-wandering may involve not only a gradual shift away from internal attention, but also a later control-related process that helps bring the episode to an end.

Together, these studies argue that mind-wandering should be understood not only as an off-task state, but as a temporally dynamic process with dissociable phases. This temporal perspective matters because the processes that initiate, sustain, and end mind-wandering may not be identical. A complete theory of mind-wandering must therefore explain not only why the mind leaves the task, but also how long it remains away and how it returns.

CHAPTER II

THE TEMPORAL DYNAMICS OF MIND-WANDERING AND META-AWARENESS

Introduction

At some point while reading this paper, you may realize that your eyes are mindlessly following the text while your thoughts have drifted elsewhere. Your mind is wandering. Mind-wandering is typically defined as a temporary attentional lapse in which focus shifts away from the current task toward self-generated thoughts (Schooler et al., 2011; Smallwood & Schooler, 2006, 2015). Although the phenomenon is often described as a momentary event, mind-wandering actually unfolds over time. In everyday situations such as reading, people move back and forth between periods of task focus and off-task thought, generating a sequence of episodes that alternate between being on-task and mind-wandering.

Extensive research has examined how common mind-wandering is, what causes it, and what consequences it carries. Far less work, however, has addressed the temporal dynamics of mind-wandering—how long episodes last and how their durations relate to one another across successive cycles of on-task and off-task activity. We argue that these dynamics are not merely a descriptive curiosity but a critical source of evidence for answering a fundamental theoretical question: Is mind-wandering supported by processes that are distinct from those supporting goal-directed, on-task mental activity? If variability in episode durations reflects variability in underlying processes, then the pattern of dynamic relationships between on-task and mind-

wandering episodes can discriminate among fundamentally different process architectures. The goal of this paper is to develop a method for measuring the duration of mind-wandering episodes and then use the resulting temporal information to adjudicate among competing models of the mind-wandering–on-task relationship.

Why Dynamics Matter

We consider three basic models of how the dynamics of on-task and mind-wandering activity may be governed. Each makes distinct predictions about the relationships among episode durations, both across individuals and within individuals over time.

Single-process model. The most parsimonious account assumes that variability in the durations of both on-task and mind-wandering episodes is governed by a single underlying process. Under this model, episode durations should be tightly related regardless of type. This model is more than a strawman account. It is plausible that an individual-specific rate-of-change factor operates relatively independently of activity type—for example, a process that regulates the length of any sustained mental activity to avoid the opportunity costs of spending too much time in any one state (Kurzban et al., 2013).

Independent-process model. Here, the durations of on-task and mind-wandering episodes are driven by separate, independent processes. The duration of one type of episode does not predict the duration of the other. This model is consistent with frameworks that posit distinct neural systems for on-task and mind-wandering states. For instance, Mittner et al.'s (2016) tripartite framework proposes that on-task focus, mind-wandering, and an intermediary state are governed by largely separate neural systems.

Opponent-process model. Like the single-process model, this model assumes a single source of variability, but with opposing effects on the two types of episodes. A natural candidate for such a factor is executive task control (Smallwood & Schooler, 2006, 2015; Thomson et al., 2015). Stronger executive control should sustain on-task focus for longer while curtailing mind-wandering episodes more quickly. As a result, the durations of on-task and mind-wandering episodes should be negatively related.

These three models represent idealized cases. More complex mixtures are possible and, in many respects, more realistic. For example, a general factor governing all durations might coexist with two additional factors that separately influence on-task and mind-wandering durations. Alternatively, on-task and mind-wandering activities might be governed by distinct processes that are in a mutually competitive relationship—combining elements of the independent and opponent models. The analytic frameworks described below are designed to detect such mixtures.

Critically, these models make predictions at two distinct but complementary levels of analysis: interindividual differences and intraindividual dynamics. We describe the predictions for each level in turn.

Interindividual Variability

Model predictions about interindividual relationships are best conceptualized within a confirmatory factor analysis (CFA) framework. This requires measuring the durations of on-task and mind-wandering episodes within at least three different contexts, which serve as indicators in the CFA. Multiple indicators serve two purposes. First, they allow us to establish a precondition for further modeling: reliable individual differences in episode durations, expressed through correlations among indicators of the same theoretical construct. Second, they allow us to

compare correlations within a construct (e.g., among on-task indicators) to correlations between constructs (e.g., between on-task and mind-wandering indicators), enabling tests of possible dissociations. Figure 1A illustrates how the three models translate into confirmatory factor structures.

The single-process model predicts that a single factor with positive loadings is sufficient to account for variability across all indicators, regardless of episode type.

The independent-process model predicts that two factors are needed—one for on-task and one for mind-wandering durations. In the case of a complete dissociation, the between-factor correlation is zero. A correlation reliably greater than zero but less than 1.0 would suggest a mixture: a general factor coexisting with type-specific factors.

The opponent-process model, in its pure form, predicts two factors with a negative correlation of –1.0. A more realistic variant—a mixture of opponent and independent processes—would yield a negative correlation between the factors that is greater than –1.0. This is the variant depicted in Figure 2.1.

Intraindividual Variability

Suppose we could measure, for each individual, the duration of every on-task and mind-wandering period, generating a time series of successive, alternating episodes. Such data would allow us to examine intraindividual dynamics: how the duration of the current episode relates to the durations of preceding episodes. If the processes governing on-task and mind-wandering durations fluctuate within individuals over time—and there is substantial evidence for meaningful fluctuations in cognitive control (Adam et al., 2015; deBettencourt et al., 2019; Mayr et al., 2013))—we can use this within-person variability to test the models against each other.

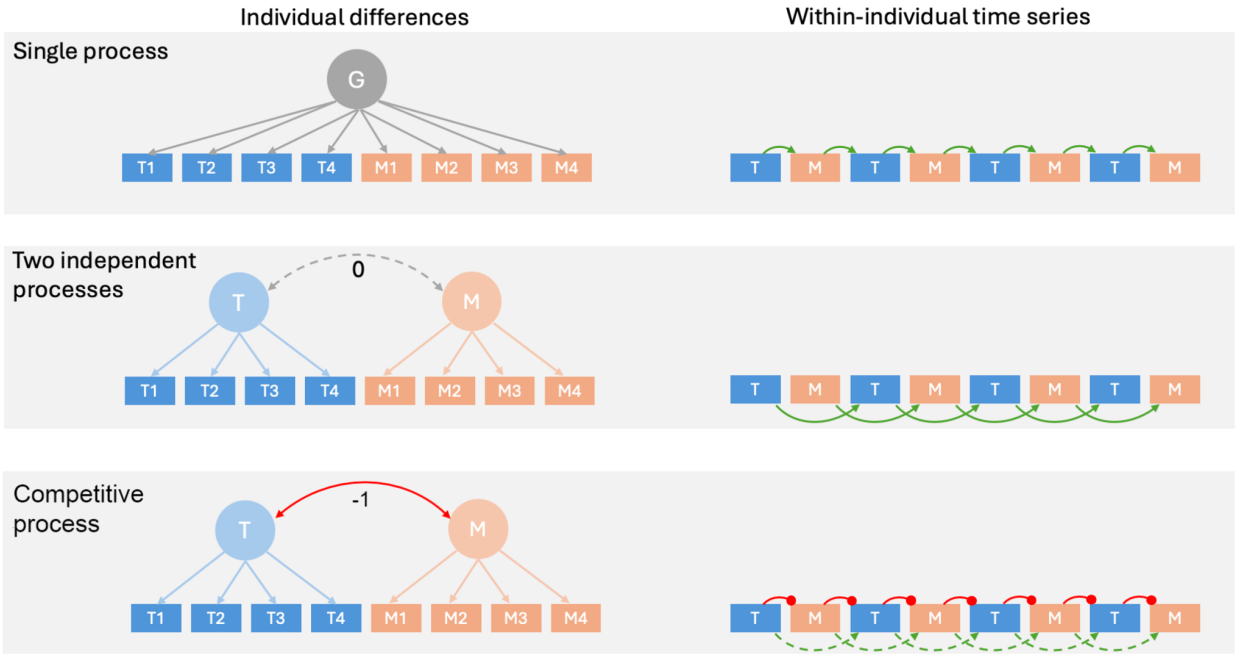
The key analytic tool is multi-level modeling with lag-1 and lag-2 durations as fixed-effect predictors, separately for on-task and mind-wandering episodes as criterion variables. Lag-1 correlations connect adjacent episodes of different types (e.g., the current mind-wandering episode with the preceding on-task episode). Lag-2 correlations connect episodes of the same type, "jumping over" the intervening episode of the other type (e.g., the current on-task episode with the previous on-task episode). Figure 2.1 illustrates these predictions.

The single-process model predicts positive lag-1 correlations only: because a single factor drives both, the current mind-wandering episode should be predicted by the duration of the immediately preceding on-task episode, and vice versa,

The independent-process model predicts reliable lag-2 autocorrelations only: because each type is governed by its own process, the duration of the current on-task episode should be predicted by the preceding on-task episode, and the current mind-wandering episode by the preceding mind-wandering episode. The emergence of both positive lag-1 and positive lag-2 correlations would indicate the coexistence of general and activity-specific factors.

The opponent-process model predicts negative lag-1 correlations: a longer on-task episode should be followed by a shorter mind-wandering episode, and vice versa, reflecting the push-pull dynamic of a single factor with opposing effects. Figure 2.1 depicts a potential mixture of independent and opponent processes—positive lag-2 correlations combined with negative lag-1 correlations.

Figure 2.1 Candidate Temporal Dynamic Models



Mind-Wandering Dynamics Are Hard to Measure

All the above models make predictions about on-task and mind-wandering durations and thus require measurement of the onset of mind-wandering episodes. Unfortunately, such an ability has mostly eluded researchers thus far (Chu et al., 2023a; Smallwood, 2013; Smallwood & Schooler, 2015). Experience-sampling methods are the most popular method to measure mind-wandering, but they are not well suited to measuring when episodes start and end (Chu et al., 2023a; Kahneman et al., 2004). So called, "probe-caught" methods occasionally interrupt participants mid-task and ask them if they were mind-wandering or on-task (Weinstein, 2018). To examine differences in an outcome variable between on-task and mind-wandering states, researchers typically categorize a temporal interval—for example, the 10 seconds prior to the probe—as mind-wandering (Smallwood & Schooler, 2006). This method risks mistakenly categorizing some amount of on-task time as mind-wandering (Voss et al., 2018).

Alternatively, self-caught methods are also occasionally used, where participants self-report whenever they realize they have been mind-wandering (Schooler et al., 2011). This method has the advantage and disadvantage of capturing meta-awareness of mind-wandering (depending on the research question measuring meta-awareness may represent a confound). Self-caught methods also categorize some amount of time prior to the self-report as mind-wandering. Thus, this method suffers from the same potential risk of mislabeling time that should have been categorized as on-task (Voss et al., 2018).

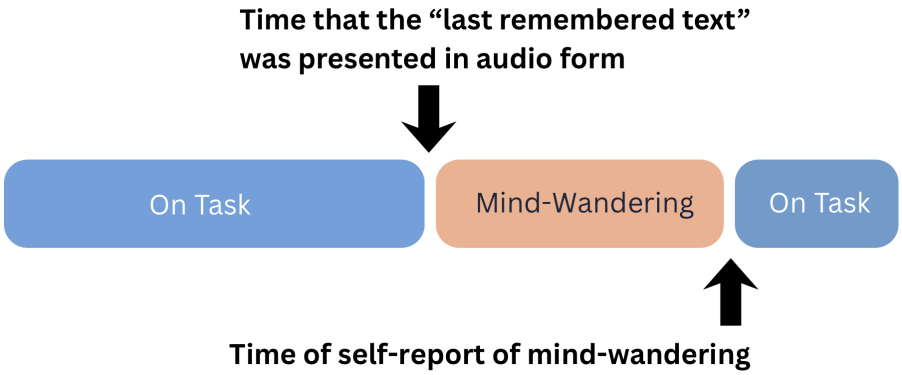
To address the onset-detection problem, a few more niche methods have attempted to derive mind-wandering onset by proxy of measuring a related variable. For instance, it is a well-established finding that timing variables on the primary task change during mind-wandering (Franklin et al., 2011; Polychroni et al., 2020). Thus, mind-wandering onset can be estimated by the point in time in a task where timing begins to change. However, because this is a proxy measure, it is not clear if the increase in reaction times actually corresponds to the true onset of mind-wandering. It may be the case that reaction times gradually increase as mind-wandering begins, meaning that some amount of mind-wandering would be mistakenly labeled as on-task. Eye-tracking is another popular method for gaining insight into covert attentional states. In the case of mind-wandering, it has proven useful for detecting mind-wandering, albeit indirectly, via differences in measures such as pupil size, and fixation duration (Faber et al., 2020; Grandchamp et al., 2014; Hutt et al., 2017; Krasich et al., 2018; Steindorf & Rummel, 2020). However, the direction and presence of these effects have been somewhat inconsistent and task-dependent (Konishi et al., 2017; Unsworth & Robison, 2016). Like the above-described reaction time method, eye-tracking also lacks a ground truth for mind-wandering onset time. Eye-behavior may not respond linearly to mind-wandering, which means that the amount of time

labeled as mind-wandering could potentially lead to vastly different findings. For example, if pupil size decreases as mind-wandering starts but then increases towards the end of the episode, a researcher using an average measure might find drastically different results depending on where in the episode their probe occurred (Konishi et al., 2017; Smallwood et al., 2011b; Unsworth & Robison, 2016).

Therefore, an important goal of the current work was to establish a method that allows for tracking the temporal dynamics of mind-wandering. Towards that end, we introduce a new mind-wandering detection paradigm that builds on top of preexisting protocols used historically to investigate mind-wandering (Chaieb et al., 2022). This paradigm is specifically designed to measure the onset of mind-wandering.

A New Way to Measure Mind-Wandering Onset

Figure 2.2 Task Structure outline



In this new paradigm, participants listen to an audiobook, an activity that reliably produces mind-wandering after some time (Feng et al., 2013; Kopp & D'Mello, 2016). While listening to the audio book, participants are instructed to press the space bar when they realize that their mind has wandered. This self-report of the realization of mind-wandering is the

traditional way that meta-awareness of mind-wandering is operationalized; the time that meta-awareness occurs also represents the end time of mind-wandering (Chu et al., 2023a). Once meta-awareness of mind-wandering is achieved, the same book that the participant was just listening to is presented in text form on the screen. Participants then indicate the last point in the text that they remembered hearing before their mind started to wander. Given that mind-wandering represents a shift of attention away from the external world towards internal thought, this "last remembered text" represents the onset of mind-wandering (Schooler et al., 2011). Importantly, because this text was delivered using audio, the exact time that the relevant text was delivered to the participant is known. Therefore, the duration of each mind-wandering episode can be calculated as the time between the "last remembered text" was delivered and meta-awareness of mind-wandering. The duration of each on-task episode can also be calculated as the amount of time from the initial audio play to the start of mind-wandering.

The Current Research

The present work has two primary aims. First, we introduce and validate our novel paradigm for detecting the onset of mind-wandering. Second, we use this paradigm to directly test three candidate models of mind-wandering temporal dynamics. These aims are addressed across two experiments.

Experiment 1. We establish the validity of our new mind-wandering detection paradigm by examining how eye-tracking markers of mind-wandering align with the onset of mind-wandering measured by our paradigm. In addition, we provide initial descriptive statistics of on-task and mind-wandering episode durations.

Experiment 2. Building on this validation, we apply our paradigm in a large-scale individual differences study to rigorously evaluate candidate models of mind-wandering temporal dynamics, both at the within and the between-individual level. Further, we examine how these temporal dynamics relate to other theoretically relevant individual differences, including working memory capacity, ADHD symptomatology, and trait mindfulness.

Experiment 1

Here, we employ eye-tracking to validate a new behavioral paradigm to detect mind-wandering onset. Eye-tracking is ideal candidate as a validation strategy because it has been well established to be sensitive to differences between on-task and mind-wandering states across a wide variety of different tasks (Faber et al., 2020; Grandchamp et al., 2014; Hutt et al., 2017; Krasich et al., 2018; Steindorf & Rummel, 2020). Therefore, should our proposed paradigm accurately track the onset of mind-wandering, we should see significant differences in eye-related measures occur at the mind-wandering onset time measured in our paradigm. Toward this end, we focus on two main eye features that are most commonly studied in the context of mind-wandering, pupil-size and fixation duration (Faber et al., 2020; Smallwood et al., 2011a; Uzzaman & Joordens, 2011).

Pupil Size

Pupil size is one of the most sensitive and temporally precise physiological markers of mind-wandering (Konishi et al., 2017; Smallwood et al., 2011a; Unsworth & Robison, 2016). Across a wide range of tasks, including reading, sustained attention, and listening tasks, pupil size reliably differentiates on-task from mind-wandering states (Faber et al., 2020; Franklin et

al., 2013; Unsworth & Robison, 2016). However, the direction of pupil-size changes associated with mind-wandering can vary across tasks (Konishi et al., 2017; Unsworth & Robison, 2016). In visually demanding tasks such as reading, mind-wandering, and inaccurate/slower responses are often accompanied by increased baseline pupil diameter (Bradshaw, 1968; Franklin et al., 2013; Gilzenrat et al., 2010; Smallwood et al., 2012). In contrast, in other high cognitive load tasks, mind-wandering has been associated with pupil constriction reflecting reduced task engagement (Grandchamp et al., 2014; Mittner et al., 2014; Unsworth & Robison, 2016, 2018).

Overall, pupil dynamics are expected to evolve continuously across the onset, maintenance, and termination of a mind-wandering episode (Konishi et al., 2017; Smallwood et al., 2011b; Unsworth & Robison, 2016). Although historically diverging findings relating to pupil size have been explained via task differences, this expected temporal dependency may also account in part for some of these inconsistent effects (Unsworth & Robison, 2016, 2018). If pupil size both decreases, and increases based on different phases of mind-wandering, then past research could find opposite effects.

For the present study, pupil size is expected to be especially informative due to static visual conditions during the experiment (Mathôt & Vilotijević, 2022). While individuals listen to an audiobook, they are to stare at a fixation cross on screen. There are no other visual elements to attend to, and no luminance changes. As such, our paradigm represents ideal conditions to measure mind-wandering related changes in pupil-size.

Fixation Duration

Fixation duration is another widely used eye-metric for characterizing mind-wandering, particularly in tasks that require active visual sampling such as reading or scene perception (Faber et al., 2020; Reichle et al., 2010; Zhang et al., 2020). Mind-wandering is typically

associated with longer fixation durations, reflecting reduced attention to visual information, reduced external perceptual processing, and disengagement from task-relevant visual input (Faber et al., 2020; Smallwood et al., 2011b; Zhang et al., 2020). During reading, for example, off-task states are reliably characterized by fewer fixations and prolonged fixation durations (Reichle et al., 2010). However, even in tasks where there are no task-relevant visual stimuli, such as listening to an audio book, mind-wandering is still associated with longer fixation durations (Faber et al., 2020).

Similarly to pupil size, fixation duration is expected to dynamically vary based on the phase of mind-wandering (Konishi et al., 2017). For example, it may be the case that fixation duration increases during mind-wandering but decreases again during meta-awareness as an individual's attentional resources are reallocated back to the task at hand.

In the present study, the audiobook listening paradigm has no task-relevant visual elements. However, previous work has found differences in fixation duration even in audio driven contexts (Faber et al., 2020; Kwok et al., 2024). Here, fixation duration effects would be driven not by visual processing demands, but instead by attentional state shifts from the environment to internal processing (Annerer-Walcher et al., 2021; Liu et al., 2022).

The Current Study

Taken together, eye-tracking provides a well-suited and theoretically grounded means of validating the proposed behavioral paradigm for identifying mind-wandering onset. Eye-movement measures offer continuous, temporally precise measures of attentional engagement that have been repeatedly shown to differentiate on-task and mind-wandering states across a wide range of different tasks.

Importantly, these measures act as an entirely independent measure of attention from mind-wandering onset times identified as part of our paradigm. Therefore, by examining pupil size and fixation duration around the estimated onset of mind-wandering, the present study tests whether established physiological signatures of mind-wandering align with the onset times produced by this new paradigm. If the paradigm accurately captures when attention shifts from the external task towards mind-wandering, we should see systematic changes in eye behavior emerge at or near the reported onset of mind-wandering.

Methods

Participants

We recruited 43 participants from the University of Oregon participant pool. Of these 43 subjects, 1 was omitted due to mid-experiment computer crash, and 4 more were omitted due to not reporting any mind-wandering episodes. Thus, data from a total of 38 participants (25 female, 12 male, 1 non-binary/third gender, mean age = 19.42 years, SD = 1.18) were used for analysis. Sample size was informed by a separate pilot experiment in which significant eye-feature x mind-wandering effects were observed with a sample of 29 participants. Accordingly, a sample of 38 participants was expected to provide sufficient power to detect comparable effects.

Material and Measures

We tested our new paradigm (described in the introduction) using segments from five different audio books, repressing five blocks. To maximize the amount of mind-wandering data, we selected books that were to be perceived as difficult or boring (Feng et al., 2013). We randomly selected 8-minute-long segments from each of the following books: *Walden* by Henry David

Thoreau, *Crime and Punishment* by Fyodor Dostoevsky, *The Republic* by Plato, *Moby Dick* by Herman Melville and *On the Origin of Species* by Charles Darwin. For each book with the exception of *On the Origin of Species* (later explained to be a buffer text to keep the experiment at a fixed duration). For each book, we created 6 reading comprehension questions. These questions involved presenting participants with two written sentences, one real sentence that was present in the audio books, and one foil. Participants were tasked with indicating which sentence was real and were monetarily rewarded for answering these questions correctly (10 cents per question). Given that the audio-book listening task is highly passive, these rewards were intended to incentivize participants to pay attention to the audio-book. Foil sentences were generated with the intent of mimicking the voice and style of each book, but described events that didn't happen. For each real sentence, a foil was randomly selected from a bank as its pair. The order that books were presented in was counter balanced.

After each mind-wandering episode participants responded to a short survey asking about the content of their mind-wandering. First, this survey asked about the type of mind-wandering (Robison et al., 2019). Here, the options were: "I was thinking about something related to the task", "I was thinking about something unrelated to the current task", "I was thinking about something in the environment", and "I was zoned out, and not thinking about anything". Next, using a 6-point Likert scale, participants indicated how pleasant or unpleasant the topic of their mind-wandering was. Finally, also using a 6-point Likert scale, participants indicate how important or unimportant the topic of their mind-wandering was. For example, an important topic might be thinking about an upcoming test, while an unimportant topic might be thinking about a movie they saw last night.

We recorded data using an Eyelink 1000 Plus while participants viewed the experiment on an Apple Mac Mini with a 24" screen (BENQ XL2411P, 60 Hz, 1920 x 1080).

Procedure

Following the completion of a consent form, participants assisted in adjusting the eye-tracker head-rest height and chair position in a dimly lit room. The eye-tracker was calibrated and validated using 9 fixation points, ensuring that during validation no more than 5 degrees of visual error per fixation. Participants were instructed to keep their eyes on the center of the fixation cross while listening to the audio books. Participants completed up to five seven-minute blocks of the mind-wandering detection paradigm, including the type of mind-wandering, valence, and real-life goal congruency follow-up questions. Each of the first four blocks guaranteed seven minutes of listening time. This time limit was paused while participants completed the post-mind-wandering segment of the task. To make this fixed experiment length possible, the final audio-book segment was considered a buffer text, and the duration of this book would be truncated based on the current elapsed experiment time. This buffer text as always *On the Origin of Species.* Therefore, the experiment always lasted at least 35 minutes (four, seven-minute listening blocks, plus one additional buffer block up to seven minutes). Not included in this time is time spent calibrating and validating the eye-tracker. Calibration and validation was repeated in between each book. In the rare case that participants reported enough mind-wandering that the 35-minute time limit elapsed prior to the completion of the 4 main books, the experiment was extended and ended immediately after the 4th block. This process ensured that for the majority of participants, the experiment would last the same amount of time regardless of how much mind-wandering was reported, and in extreme cases, a minimum amount of extra time was added so that all participants experienced the exact same amount of listening time.

Following each block, participants were presented with the reading comprehension questions from the book they just finished listening to. After completing these questions, they received feedback displaying how much money they earned from the prior questions, and then were given the opportunity to take a short break.

Finally, it was made clear to participants that mind-wandering was not a "bad thing", and that participants should not feel bad for reporting lots of mind-wandering. It was also made clear that reporting lots of mind-wandering would not extend the duration of the experiment.

Data-Processing and Modeling

Eye-data was down-sampled to 200Hz prior to analysis. Blinks were removed and surrounding pupil size measurements were smoothed using a rolling median with a width of 15 samples. For pupil size, a pupil-size deviation measure was computed by subtracting a subject's mean pupil size over the course of the entire recording session from each sample. Mind-wandering episodes that lasted less than or equal to four seconds were removed from all analyses due to later models requiring mind-wandering episodes to be longer than four seconds. Extremely long mind-wandering episodes (>50 seconds) were also omitted from analyses. To account for reaction time in indicating meta-awareness, the last second of each mind-wandering episode was omitted from analysis.

Our modeling strategy aimed to resolve challenges that arise from mind-wandering episodes differing in their start time, duration, and end time. Simply aligning episodes to mind-wandering start time would miss patterns that might arise with the cessation of mind-wandering. Additionally, the variable durations of mind-wandering episodes represent yet another modelling challenge. For example, using a "time until mind-wandering ends" variable will capture drifts in

eye behavior, but might miss discrete changes that happen near the end of mind-wandering. For these reasons, we settled on the following segmented, multi-level modeling strategy:--

$$\begin{aligned}\text{EyeMeasure}_{ijk} = \beta_0 &+ \beta_1 \text{TimeUntilMW}_{ijk} + \beta_2 \text{MWMaintenance}_{ijk} \\ &+ \beta_3 \text{MAInterval}_{ijk} + \beta_4 \text{MWStep}_{ijk} + \beta_5 \text{MAStep}_{ijk} \\ &+ b_{0k}^{(\text{Subject})} + b_{0jk}^{(\text{Episode})} + \varepsilon_{ijk}\end{aligned}$$

In this model, Time Until MW is negative, counting to 0 corresponding to wandering onset. This variable captures gradual shifts as individuals slip from on-task focus into mind-wandering. MW Maintenance captures patterns relating to the middle of mind-wandering, or in otherwards, as mind-wandering is "maintained" over time; it is set to 0 until mind-wandering begins, wherein it begins to count up until the last 4 seconds of mind-wandering which is reserved for the next segment. MA Interval is used to measure effects that occur in relation to the end of mind-wandering, and in this experiment's case, meta-awareness. This variable counts backwards in time 4 seconds from mind-wandering end and is then set to 0 in all other times. Due to the above-described removal of the last second of mind-wandering for reaction time, this variable contains only 3 seconds worth of data, but measures 4 seconds prior to the end of mind-wandering. Given that the exact timing of meta-awareness related processes is not currently known, this 4 second window was chosen as a liberal interval to ensure meta-awareness related changes would be captured. To capture discrete, step-wise changes that occurs when mind-wandering starts, MW Step is set to 0 during on-task focus, and 1 during mind-wandering, Similarly, to capture the same potential step-wise changes that occur in relation to meta-awareness, MA Step is set to 0 up until the last 4 seconds of a mind-wandering episode, wherein it changes to 1 (again, containing 3 seconds worth of data here).

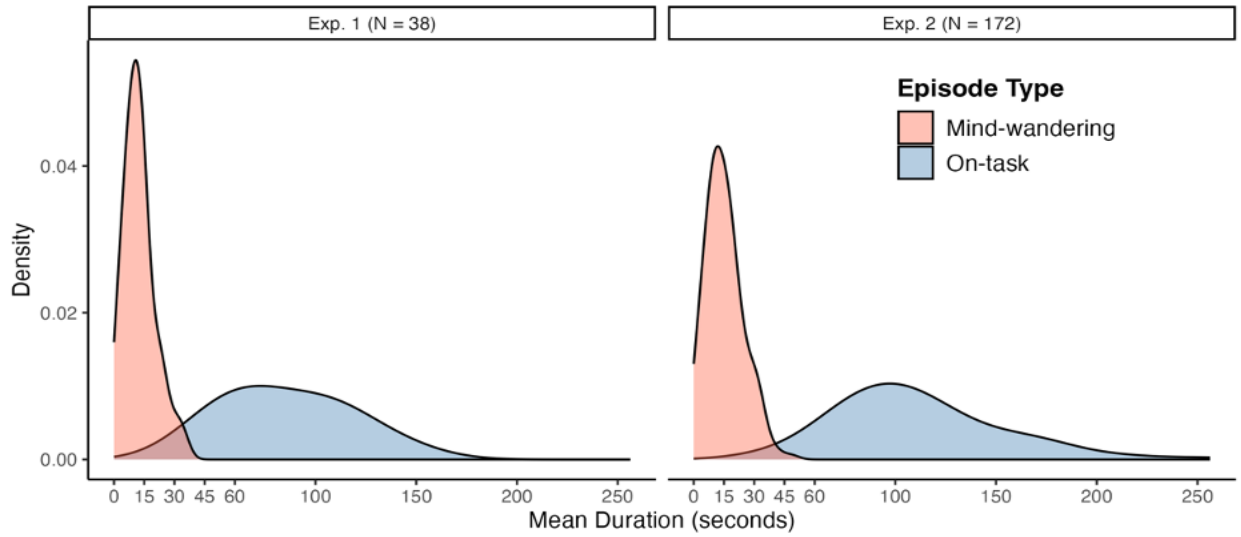
Taken together, this segmented approach addresses the challenge of mind-wandering episodes being extremely heterogenous in their timing. The described model allows for detection of effects relating to all parts of the mind-wandering anatomy, capturing the drift into and maintenance of mind-wandering, as well as the cessation of mind-wandering via meta-awareness.

Results

Episode Descriptive Statistics

Given that this is the first time that mind-wandering and on-task episode length has been measured directly, we started our analysis by examining episode lengths. The average subject average duration for on-task episodes was 85.4 seconds (mean SD = 43.04 seconds), and the average duration for mind-wandering episodes was 12.5 seconds (mean SD = 7.35 seconds). Figure 2.3 shows distributions of on-task and mind-wandering episode lengths. Out of all mind-wandering episodes across all subjects, the proportion of mind-wandering topics were as follows: 34.1% task unrelated, 27.7% task related, 14.1% environmental, and 24.1% zoning out.

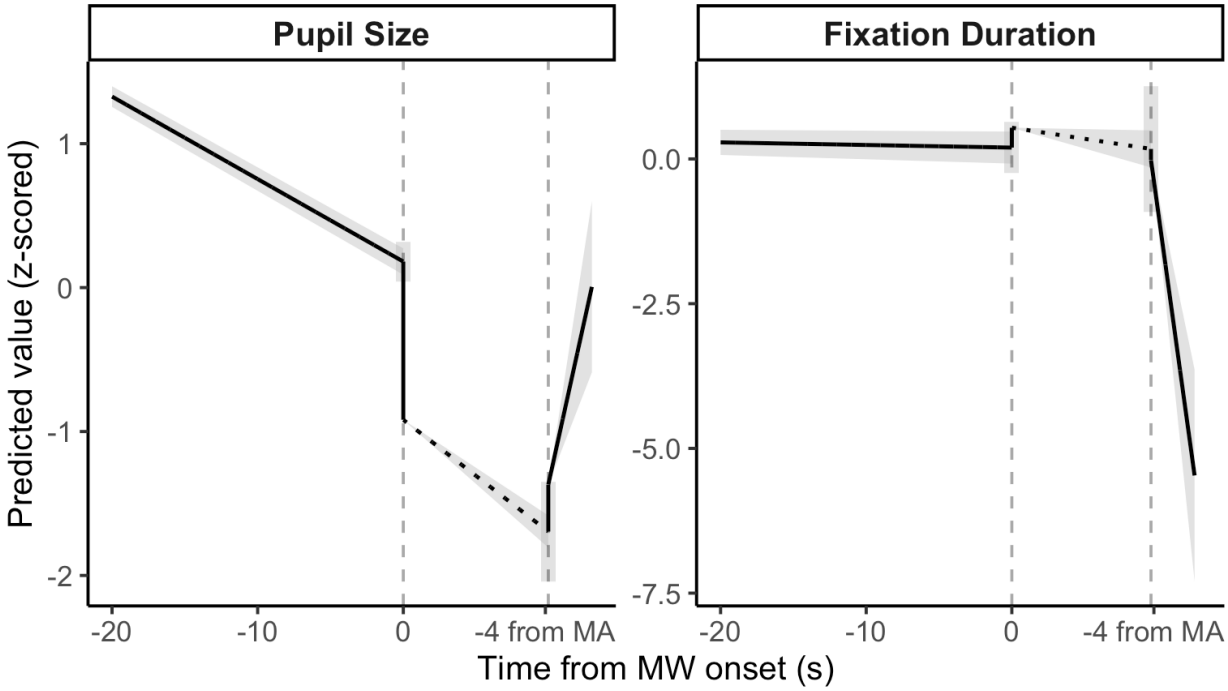
Figure 2.3 Distribution of Mean Episode Durations



Eye-Metrics

To characterize how eye behavior evolves across the onset, maintenance, and termination of mind-wandering, we fit multi-level segmented regression models to pupil size, fixation duration, and saccadic amplitude. All models included fixed effects corresponding to distinct temporal segments of mind-wandering—pre-onset drift (*Time Until MW*), within-episode maintenance (*MW Maintenance*), and pre-termination dynamics (*Time Until MA*)—as well as step-wise indicators of mind-wandering onset (*MW Step*) and proximity to meta-awareness (*MA Step*). Random intercepts were specified for episodes nested within subject.

Figure 2.4 Predicted Eye Dynamics During an Average Mind-Wandering Episode



Pupil size

For pupil-size, we computed a pupil-size deviation variable calculated by subtracting each individuals' average pupil size over the entire experiment from each sample. Pupil size showed significant effects across all phases of mind-wandering (Figure 2.4). Consistent with gradual disengagement from task-focused attention, pupil size decreased as participants approached mind-wandering onset (*Time Until MW*: $\beta = -1.40$, $t = -115.25$, $p < .001$). When mind-wandering began, there was a step-wise decrease in pupil size (*MW Step*: MW Step: $\beta = -26.83$, $t = -15.65$, $p < .001$). Following onset, pupil size continued to decrease throughout the maintenance phase of mind-wandering (*MW Maintenance*: $\beta = -1.90$, $t = -13.65$, $p < .001$), indicating sustained changes during internally focused attention.

Pupil size exhibited a pronounced reversal as mind-wandering episodes approached their end via meta-awareness. In the final four seconds prior to mind-wandering end, pupil size increased linearly (*Time Until MA*: $\beta = 11.21$, $t = 4.54$, $p < .001$), but significant showed no step-wise increase (*MA Step*: $\beta = 7.96$, $t = 1.85$, $p = .064$).

Fixation duration

Fixation duration showed more modest effects across phases of mind-wandering. As participants approached mind-wandering onset, fixation durations shortened (*Time Until MW*: -0.37, $t = -3.01$, $p = .003$). As mind-wandering started, fixation duration did not significantly change (*MWStep*: $\beta = 28.20$, $t = 1.54$, $p = .124$). In contrast to this, during the maintenance phase, fixation duration decreased over time (MW Maintenance: $\beta = -3.15$, $t = -2.25$, $p = .025$). There was no significant step-wise meta-awareness related change (MA Step: $\beta = -15.70$, $t = -0.35$, $p = .729$). However there was a significant linear decrease in fixation duration in the final four seconds prior to meta-awareness (Time Until MA: $\beta = -149.58$, $t = -5.85$, $p < .001$).

Discussion

We designed a novel mind-wandering detection paradigm to estimate the on-set time of mind-wandering from purely behavioral data. In summary, while listening to an audio-book, participants self-reported meta-awareness of mind-wandering. Then, they were asked to report the point in the audio that they last remembered hearing prior to becoming lost in thought. The timestamp of this "last-remembered-text" is used here as a measure of mind-wandering onset. To validate this new approach, we use eye-tracking to measure several eye-related data points, and time-locked these features to mind-wandering onset as measured by our new paradigm. Pupil size gradually decreased, leading up to mind-wandering, dropped sharply at onset, decreased

during mind-wandering maintenance, and then increased again prior to meta-awareness. This pattern reflects both disengagement from the task and subsequent re-engagement via meta-awareness.

These results provide support for the validity of our behavioral mind-wandering onset paradigm. Eye-tracking measures captured fine grained temporal signatures of attentional shifts relating to mind-wandering, demonstrating that the "last-remembered-text" measure aligns with well-established physiological markers of mind-wandering.

Experiment 2

Having established a method for measuring the durations of on-task and mind-wandering episodes, we next turn to modeling the dynamics governing these two states. Specifically, Experiment 2 provides an explicit test of three candidate models of mind-wandering temporal dynamics: the **single-process**, **independent-process**, and **opponent-process** models.
In addition to testing these models, we examine how several commonly studied individual difference factors relate to the durations of on-task and mind-wandering episodes. Prior research has identified reliable relationships between mind-wandering frequency and traits such as working memory capacity, ADHD symptoms, and trait mindfulness. However, because past work has not measured on-task and mind-wandering episode durations, it remains unclear whether these traits influence the length of on-task episodes, the length of mind-wandering episodes, or both.

Higher working memory capacity typically decreases the amount of mind-wandering, however this effect is not ubiquitous, and instead appears to sometimes be task dependent. In situations where the primary task is demanding, higher working memory capacity correlates with

reduced mind-wandering; however, in cases where the primary task requires less cognitive load, other work shows that higher working memory capacity can predict more mind-wandering (Levinson et al., 2012; Rummel & Boywitt, 2014). Although other work has contested this idea (Robison & Unsworth, 2017). Regarding the present experiment, it is also unclear if working memory capacity correlates with on-task durations, mind-wandering durations, or both.

Another individual difference factor that has shown a more consistent directional effect is ADHD, where individuals at high risk for having ADHD report mind-wandering more often (Franklin et al., 2017; Lanier et al., 2021; Seli et al., 2015). However, it is again unclear if this means that individuals with ADHD have shorter on-task episode durations, longer mind-wandering durations, or both.

Finally, we also examine how differences in trait level mindfulness correlate with episode duration. Mindfulness practices have become increasingly popular over the last few decades, and higher levels of mindfulness have consistently been shown to predict less mind-wandering (Belardi et al., 2022; Turkelson & Mano, 2022). Yet the exact nature of this relationship remains unclear. Higher levels of mindfulness could reflect an enhanced ability to sustain attention (resulting in longer on-task episodes), a greater capacity to notice mind-wandering once it begins (resulting in shorter mind-wandering episodes), or both.

Taken together, Experiment 2 has two primary goals. The first, primary aim is to provide a rigorous test of mind-wandering temporal dynamics by evaluating the empirical support for three candidate models: the single-process, independent-process, and opponent-process models. The second goal is to clarify how commonly studied individual difference factors relate to mind-wandering by examining whether these traits differentially predict the durations of on-task and mind-wandering episodes

Methods

Participants

We recruited 198 participants from the University of Oregon participant pool. Our pre-registration prescribed removing any subjects with incomplete or missing data, for these reasons, data from 20 participants was excluded from analysis. Data from 178 participants (122 female, 53 male, 3 non-binary/third gender, mean age = 19.1 years, SD =1.95) were used for analysis. Previous work has found differences in correlations between r=.0 and r=.3 (Faul et al., 2007; Robison & Unsworth, 2018; Voss et al., 2018). To detect such an effect with a power of .80, we require a sample size of 172 participants. The experimental predictions require a sample size of 90, calculated based on repeated measures within factor ANOVA, with a detectable effect size of f = .15 and a power of .80. Therefore, 178 participants is sufficient to examine all the predictions tested in this experiment.

Material and Measures

The audiobook segments and post–mind-wandering survey used in Experiment 1 were used again here. The only difference was the duration of the listening blocks: in Experiment 2, blocks lasted 8 minutes instead of 7 minutes, resulting in a total listening duration of 40 minutes.

Working memory capacity was assessed using the digit span, arrow span, and symmetry span tasks (Foster et al., 2015;Oswald et al., 2015), which were administered through a Java-based desktop application. ADHD symptoms were measured with the Adult ADHD Self-Report Scale (ASRS-v1.1), and trait mindfulness was assessed using the Mindful Attention Awareness Scale (MacKillop & Anderson, 2007; Kessler et al., 2005). Participants also completed three questions about their meditation experience. To assess current practice, they were asked, “How often do you

currently meditate?" using a six-point Likert scale ranging from "Never" to "Everyday." To assess past practice, they were asked, "In the past, was there ever a time when you meditated consistently?" with the same response options. Finally, to measure the duration of their meditation habits, participants were asked, "What's the longest period of time in your life that you've consistently meditated?" with response options ranging from "I've never consistently meditated" to "Longer than a year."

Procedure

Following informed consent, participants completed up to five 8-minute blocks of the mind-wandering detection paradigm (Fig. 1). As in Experiment 1, the first four blocks each guaranteed 8 minutes of listening time. The timer paused while participants completed the post–mind-wandering follow-up questions. The final audiobook segment (On the Origin of Species) served as a buffer text, allowing the experiment to maintain a fixed duration by truncating the final block as needed. As a result, the listening portion of the experiment always lasted 40 minutes.

Participants were informed that after listening to each audiobook they would complete reading-comprehension questions based on the material. They were told that correct answers would be monetarily rewarded, but that the reward value would vary across books: questions were worth either $0.01 or $1.00 each. Prior to the start of each audiobook segment, participants were informed how much the questions associated with that book would be worth. This reward discrepancy served as the primary experimental manipulation, making some audiobook segments more valuable to attend to than others.

Participants were also explicitly told that mind-wandering was not a "bad" outcome, and that they should report it honestly. It was further emphasized that reporting mind-wandering would not extend the duration of the experiment.

After completing the audiobook task, participants were given a short break before completing the working-memory assessment. The three working-memory tasks were always administered in the same order (rotation span → operation span → symmetry span). Finally, participants completed an online questionnaire including the ASRS-v1.1, the MAAS, the meditation experience questions, and demographic items.

Results

We first wanted to examine the descriptive statistics of episode lengths, and compare them to the lengths found in Exp. 1. Using a two-step aggregation process to first get subject means and standard deviations, then averaging those values together we found that the average on-task episode lasted 106.31 seconds (SD = 64.56), and the average mind wandering episode lasted 16.44 seconds (SD = 9.36) (Fig. 1). Although not explicitly measured in the past, these averages do broadly align with past research that has attempted to estimates mind-wandering duration (Varao-Sousa et al., 2017; Voss et al., 2018). To account for the possibility that individuals are sometimes "missing" mind-wandering and not reporting it, we tested the normality of the on-task durations (after log transforming them). If individuals were consistently not reporting mind-wandering, one would expect a salient right skew in on-task durations, as the next time that mind-wandering was reported, the previous episode labeled as on-task would include multiple on-task and mind-wandering episodes. A Shapiro-Wilk normality test resulted in no evidence that on-task durations are non-normal ($W = 0.99$, p-value = 0.133).

Mind-Wandering Content

Next, regarding the content of mind-wandering episodes, using the same two step aggregation process we found 39.5% of mind-wandering to be TUTs, 21.1% TRTs, 17.4% environmental distraction, and 22.0% zoned out. Mind-wandering valence and importance were judged on a 6 point Likert scale; after centering responses, the average valence of mind-wandering was 0.052 (SD = 1.04), and the average importance of mind-wandering content was 0.014 (SD =1.23). This suggests that in our experiment mind-wandering was not particularly skewed towards one end of the valence of importance scales. In a model predicting mind-wandering duration by the reported valance of that episode we found that positively valenced episodes lasted longer (b =0.070, SE =0.017, t = 3.946, p <.001) but there was no effect of reported importance (b =0.023, SE =0.016, t = 1.411, p = 0.158).

In an unregistered analysis, we examined how the emotional valence of an upcoming mind-wandering episode predicted the duration of the preceding on-task episode. The model revealed a significant positive linear effect of valence (b=0.056, SE=0.013, t=4.33, p<.001) indicating that on-task episodes tended to last longer when the subsequent mind-wandering episode was more positively valenced, and correspondingly shorter when the upcoming episode was more negatively valenced. In addition, there was a small but significant negative quadratic effect (b=−0.022, SE=0.010, t=−2.30, p=.022). This suggests that extremely valenced mind-wandering episodes (strongly positive or strongly negative) tended to follow somewhat shorter on-task periods than more moderately valenced episodes.

Structural Equation Modeling

The hypothesized structural equation model included four latent variables for mind-wandering (MW) duration (one for each audiobook), four latent variables for on-task duration (one per audiobook), three latent variables representing working memory capacity (operation span, symmetry span, and rotation span tasks), and three latent variables each for ADHD symptoms and trait mindfulness (derived from item parcels of the respective questionnaires).

First, we fit a measurement model in which on-task duration, mind-wandering duration, working memory capacity, ADHD symptoms, and trait mindfulness were each modeled as latent factors. On-task and mind-wandering duration factors were defined by episode durations from each of the four audiobooks, working memory capacity was defined by performance on the operation span, symmetry span, and rotation span tasks, and ADHD symptoms and trait mindfulness were defined by three item parcels from their respective questionnaires. The measurement model provided excellent fit to the data ($\chi^2(109) = 125.296$, $p = .136$, CFI = .987, TLI = .984, RMSEA = .029, 90% CI [.000, .050], SRMR = .045). All item indicators loaded significantly onto their respective latent factors, all ps < .001. Standardized loadings for the on-task duration factor ranged from .601 to .754, and loadings for the mind-wandering duration factor ranged from .785 to .880, indicating reliable within-state consistency across audiobooks. Standardized loadings ranged from .628 to .764 for working memory capacity, .779 to .905 for ADHD symptoms, and .780 to .804 for trait mindfulness, suggesting that the psychometric indicators also cohered well with their respective latent constructs.

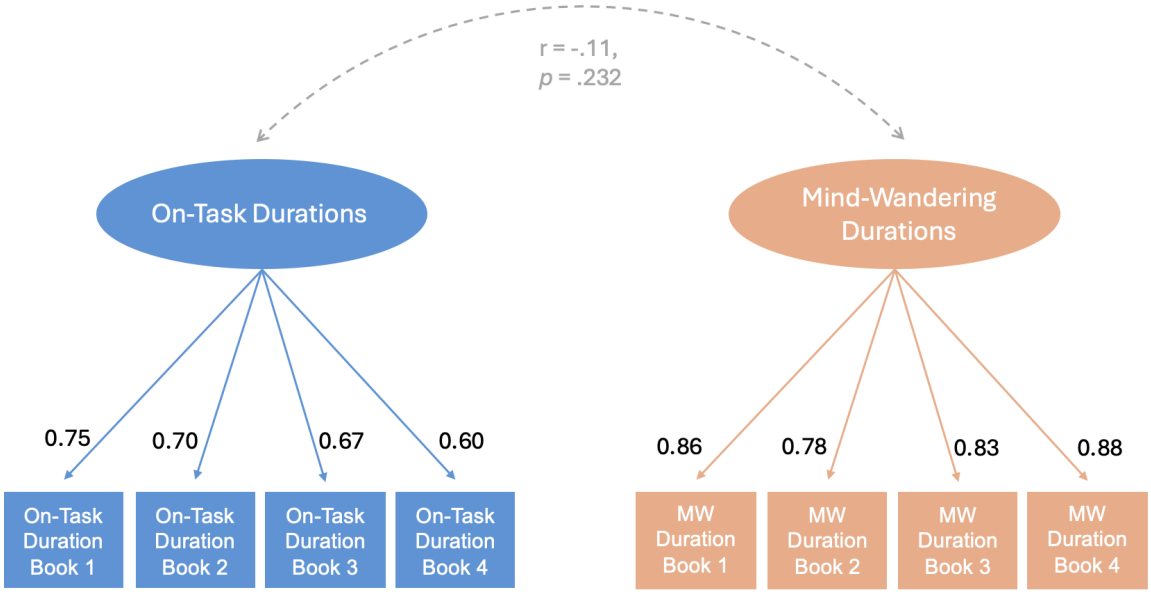
In the second step, we fixed the factor loadings to the values estimated in the measurement model and examined the relations among the latent constructs. This fixed-loading model also provided excellent fit to the data ($\chi^2(121) = 125.296$, $p = .376$, CFI = .997, TLI =

.996, RMSEA = .014, 90% CI [.000, .040], SRMR = .045). Critically, on-task and mind-wandering duration were not significantly associated (β = −.109, *p* = .232), indicating that individuals who tended to remain on task for longer periods did not reliably differ in the duration of their mind-wandering episodes. This dissociation provides evidence for the independent-process model, in which on-task and mind-wandering durations reflect separable temporal tendencies rather than opposite ends of a single duration process. ADHD symptoms were negatively associated with on-task duration (β = −.293, *p* = .002), and positively associated with mind-wandering duration (β = .168, *p*= .048). Trait mindfulness showed the opposite pattern, positively correlating with on-task duration (β = .256, *p* = .008), and negatively correlating with mind-wandering duration (β = −.188, *p* = .034). Working memory capacity was positively associated with mind-wandering duration (β = .204, *p* = .031), but was not significantly associated with on-task duration (β = −.127, *p* = .207). Between the individual-difference constructs, ADHD symptoms and trait mindfulness were strongly negatively associated, β = −.768, p < .001. In contrast, working memory capacity was not significantly associated with either ADHD symptoms, β = −.025, p = .788, or trait mindfulness, β = .035, p = .716.

As a sensitivity analysis, we repeated the two step SEM model after restricting the mind-wandering episodes to episodes participants explicitly identified as task-unrelated thoughts. This model also showed acceptable-to-good fit to the data ($\chi^2(121) = 140.795$, p = .105, CFI = .982, TLI = .979, RMSEA = .030, 90% CI [.000, .050], SRMR = .054). The relationship between on-task and mind-wandering durations remained nonsignificant (β = −.049, p = .620). Thus, even when the mind-wandering factor was restricted to “true” task-unrelated thought episodes, individuals with longer on-task episodes did not reliably differ in the duration of their mind-wandering episodes.

Overall, these SEM results most strongly support an independent-process model, in which the durations of on-task and mind-wandering episodes represent separable latent constructs that are influenced in opposite directions by individual differences in attention-related traits.

Figure 2.5 SEM Path Diagram



Within-Individual Models

Next, we examined the temporal dynamics of episode durations. Our lag model consisted of predicting the current episode duration by the lag-1 and lag-2 durations interacting with episode type (mind-wandering/on-task). Irrespective of episode type, the duration of the previous episode of the same type (lag-2) positively predicted the current episode (b = 0.183, SE = 0.028, t = 6.507, p < .001), while longer preceding episodes of the opposite type was associated with shorter current episodes (b = −0.216, SE = 0.027, t = −7.92, p < .001). The lag-2 durations interacted with episode type, where longer mind-wandering durations were then again followed

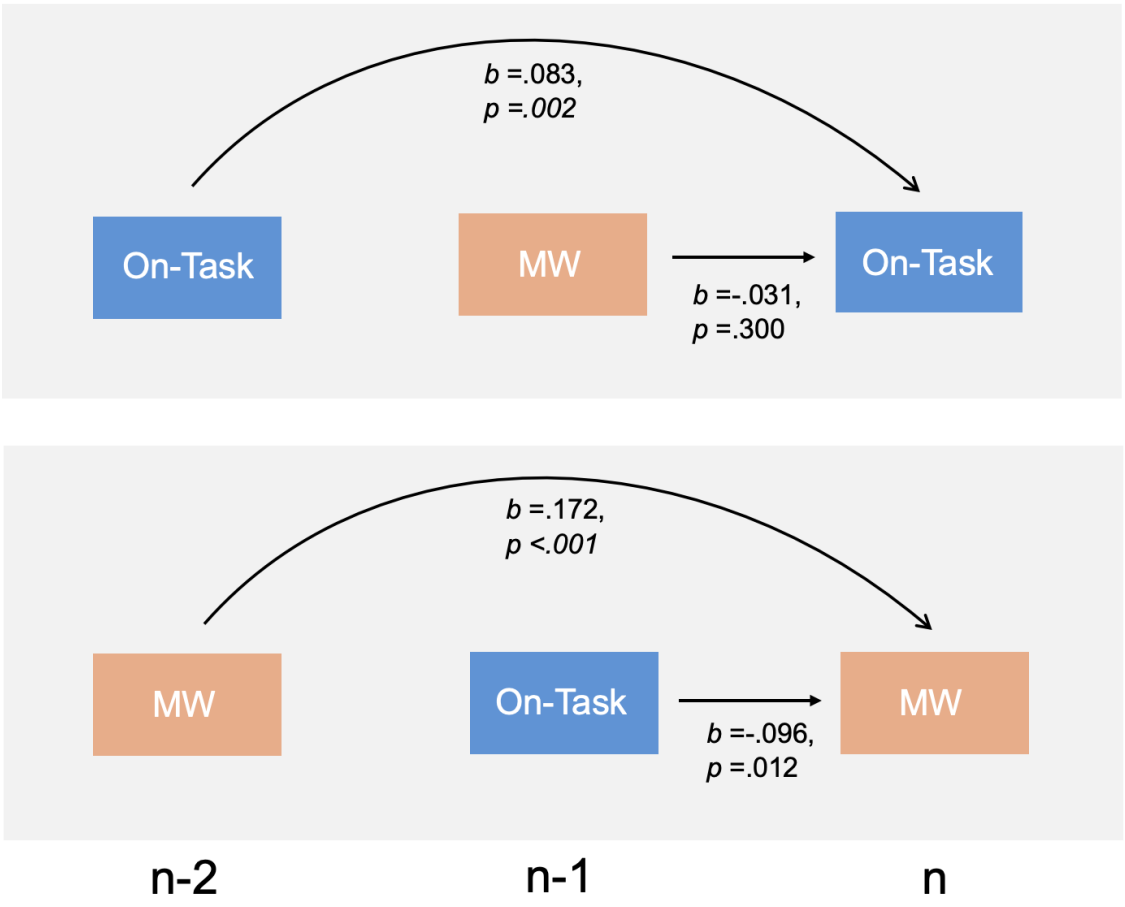
by longer mind-wandering durations (b = .259, SE = 0.039, t = 6.721, p < .001) but there was no interaction between episode type and lag-1 durations (b = -0.048, SE = 0. 040, t = - 1.199, p = 0.231). This pattern indicates negative lag1 coupling and positive lag2 autocorrelations: long episodes tend to be followed by shorter episodes, but then longer subsequent episode of the same type. Such dynamics are consistent with an opponent-process model, in which MW and on-task processes compete for shared cognitive resources, rather than the single-process model (which predicts positive lag-1 coupling) or independent-process model (which predicts no lag-1 effect).

Moving beyond our preregistered lag model, we next decomposed the lag effects into their directional components to further clarify the temporal dependencies between mind-wandering and on-task episodes. Specifically, lag-1 effects were split into previous mind-wandering duration predicting current on-task duration and previous on-task duration predicting current mind-wandering duration, while lag-2 effects were split into previous on-task duration predicting current on-task duration and previous mind-wandering duration predicting current mind-wandering duration. This model was fit with a maximal random-effects structure for the directional lag terms and episode type. The split-lag model revealed that the negative lag-1 effect was asymmetric: longer previous on-task episodes significantly predicted shorter subsequent mind-wandering episodes (b = −0.097, SE = 0.038, t = −2.527, p = .013), whereas previous mind-wandering duration did not significantly predict the duration of the following on-task episode (b = −0.032, SE = 0.030, t = −1.051, p = .296). In contrast, both lag-2 effects were positive and significant: longer previous on-task episodes predicted longer subsequent on-task episodes (b = 0.083, SE = 0.027, t = 3.087, p = .002), and longer previous mind-wandering episodes predicted longer subsequent mind-wandering episodes (b = 0.172, SE = 0.044, t = 3.939, p < .001). Thus, the directionally decomposed model qualified the opponent-process

component: the negative lag-1 effect was primarily driven by the extent to which sustained on-task focus predicted shorter subsequent mind-wandering, whereas positive lag-2 autocorrelation was observed for both mind-wandering and on-task states.

As a sensitivity analysis, we repeated this split-lag model after restricting mind-wandering episodes to those identified as task-unrelated thought. This model produced the same overall pattern as the primary analysis. For the lag-1 effects, longer previous on-task episodes predicted shorter subsequent mind-wandering episodes ($b=-0.253$, $SE=0.070$, $t=-3.625$, $p<.001$) whereas previous mind-wandering duration did not predict the duration of the following on-task episode ($b=-0.020$, $SE=0.039$, $t=-0.520$, $p=.603$). Positive lag-2 effects also remained significant for both on-task episodes ($b=0.180$, $SE=0.045$, $t=4.000$, $p<.001$), and mind-wandering episodes, ($b=0.473$, $SE=0.077$, $t=6.157$, $p<.001$).

Figure 2.6 Lag Model Relationships



Working memory capacity was tested as a moderator of these lag effects (using the original pre-registered lag model structure) by including it as an additional interaction term in the above-described model. There was a significant three-way interaction among working memory capacity, episode type, and lag-2 episode duration ($b = -0.165$, SE = 0.042, $t = -3.97$, $p < .001$). This suggests that individuals with higher working memory capacity were less influenced by the duration of previous mind-wandering episodes meaning that working memory capacity might "protect" against falling into rhythms of long mind-wandering durations. There was no interaction effect between ADHD or MAAS and any lag duration (ADHD, Lag-1: b =0.010, SE =0.041 , t = 0.137, p = 0.891; ADHD, Lag-2: b =-0.035, SE = 0.0390, t = -0.900, p =0.368;

MAAS, Lag-1: *b* =0.015, SE =0.062 , t =0.242 , p =0.809;MAAS, Lag-2: *b* =-0.00, SE =0.052 , t =-0.035 , p =0.972).

Finally, we assessed effects from our reward manipulation, hypothesizing that reward would increase on-task durations, decrease mind-wandering durations, or both. We found no effect in a model predicting current episode duration by the interaction between reward and episode type, (*b* = −0.00, SE = 0.00 t = -0.498, p = 0.618). We also tested to see if reward interacted with the reported importance of the mind-wandering topic hypothesizing that maybe these two sources of value needed to be balanced, but we found no such interaction effect (*b* =-0.00 , SE =0.00 t = -0.643, p = 0.520) Following these null results, in an exploratory model we tested to see if working memory capacity might interact with episode type and reward, wherein an individual with higher working memory capacity would be able to maintain the relevance of the higher reward more than individuals with less working memory capacity; but we again found no interaction effect (*b* = 0.00, SE = 0.00 t = 1.231, p = 0.218). Lastly, we examined if reward instead interacted with lag durations, affecting the overall temporal rhythm of attention as opposed to mean episode durations. We again found no evidence of reward interacting with any lag duration (Lag-1: *b* = -0.00, SE = 0.00 t = -0.415, p = 0.678; Lag-2: *b* = 0.00, SE = 0.00 t = 0.474, p = 0.635).

Discussion

During everyday tasks such as reading, people naturally move back and forth between periods of on task focus, and mind-wandering. This means that mind-wandering is an inherently dynamic phenomenon that unfolds over time. We argue that any complete theory of mind-

wandering should thus be able to account for these temporal dynamics. However, existing research on mind-wandering has not yet addressed this question of dynamics, mainly due to methodological limitations that have precluded the ability to measure when mind-wandering starts. Without a measure of mind-wandering onset, both the duration of on-task focus, and the duration of mind-wandering episodes are unknown. To address this limitation, we present a new behavioral paradigm, validated with eye-tracking, that allows estimation of the time of mind-wandering onset with an unprecedented degree of temporal accuracy. In summary, this new method takes advantage of the natural way in which individuals combat mind-wandering in real life. While listening to an audio book, participants self-report whenever they had realized they were mind-wandering (meta-awareness) then, they are presented with text of the audio that they were just listening to and they are asked to report the portion of the text that they last remember hearing prior to starting to mind-wander. This is the exact same process that unfolds in everyday life when reading a book. When one realizes they have been mindlessly reading, they simply scan backwards in the text to resume reading at the point prior to mind-wandering. Using this new measure, we propose three candidate abstract models of mind-wandering temporal dynamics—single process, independent process, and opponent process. We examine these models at two independent levels of analysis: an individual-difference level and a within-individual level. At the individual-difference level, the independent-process model had the most support. At the within-individual level, the results again supported an independent-process model, but also revealed an additional competitive component between those two processes. We additionally measured a number of control related traits to correlate with on-task and mind-wandering durations and found the majority of them to correlate in the expected directions (i.e.

higher control led to longer on-task durations, and shorter mind-wandering durations). Below we integrate these findings into the broader mind-wandering literature.

Individual Differences

The first step in our analysis involved using structural equation modeling to specifically test if on-task focus, and mind-wandering states represent separate latent factors—a single factor emerging here would have been evidence of a single process model. We found separate latent factors for both states, and importantly, no relationship between them. Such a pattern matches what would be expected under an independent process model. While the relationship between the two factors was not significant, it was negative, which is the expected direction of an opponent process model. However, our study was sufficiently powered to detect even small correlations. Nevertheless, because this is the first time on-task durations and mind-wandering durations have been explicitly examined, it will be important for future work to replicate this finding. This finding that mind-wandering and on-task focus appear to represent two, independent processes most aligns with previous work done by McVay and Kane (2009, 2012) and Mittner et al. (2016). McVay and Kane propose that mind-wandering occurs due to failures in cognitive control, but the length of mind-wandering episodes do not necessarily affect on-task episodes length. This implies that mind-wandering durations are controlled by a separate, independent process. Similarly, Mittner and colleagues' (2016) proposed a tripartite framework, which posits that on-task and mind-wandering states are governed by largely separate neural systems. However, it is important to note here that Mittner and colleagues' framework also includes a third, intermediary state that controls the transition between on-task and mind-wandering states.

Our study had no way of measuring this potential third state, but our structural equation results do support mind-wandering and on-task focus being independent processes.

Also, on the individual difference level but representing a separate research question is how traits like working memory capacity, ADHD, and mindfulness relate to on-task and mind-wandering durations. Previous research has largely agreed that each of these traits are associated with mind-wandering, but it has yet to be examined if these traits result in longer on task durations (i.e. lower mind-wandering frequency) or shorter mind-wandering episodes.

One somewhat puzzling aspect of these results was that ADHD symptoms and trait mindfulness showed opposite patterns of association with on-task and mind-wandering durations, a pattern that is not cleanly mapped to the independent-process model. There are at least two possible post-hoc explanations for this finding. First, ADHD symptoms and trait mindfulness may not be homogeneous constructs, and different subdimensions may map uniquely onto each duration factor. This possibility is consistent with the ADHD literature, which has distinguished between partially separable symptom dimensions, including inattention, hyperactivity, and impulsivity (Span et al., 2002). Although the mindfulness measure used in the current experiment, the MAAS, was designed as a single-factor scale (Brown & Ryan, 2003), mindfulness more broadly has often been modeled as a multidimensional construct, including facets such as observing, describing, acting with awareness, nonjudging, and nonreactivity (Baer et al., 2006).

Second, the relation between on-task and mind-wandering duration may not be truly zero. Although this association was not statistically significant at the between-person level, the estimated correlation was negative. At the within-individual level, the lag analyses provided some evidence of competition between on-task and mind-wandering durations over time.

Therefore, it is possible that there is a small competitive relationship between these two duration factors that the present sample was not large enough to detect reliably.

Working memory capacity did not correlate as expected; there was no significant relationship between higher working memory capacity and on-task durations and if anything trended towards shorter on-task durations. Additionally, those with higher working memory capacity reported longer mind-wandering durations, again in the opposite direction than what was expected. However, this result is not entirely inconsistent with the literature; it has been established that the relationship between mind-wandering and working memory capacity can be highly context dependent, with undemanding tasks not uncommonly resulting in a positive correlation between mind-wandering and working memory (Levinson et al., 2012; Rummel & Boywitt, 2014). Although we selected texts to be relatively difficult, the task of passively listening to an audiobook could be considered undemanding, thus explaining our findings. An additional, separate explanation could stem from the unique relevance of meta-awareness in our task. Not only do participants need to self-report when mind-wandering happens, but they also self-report where mind-wandering began. There is preliminary work that suggests a positive association between working memory capacity and meta-awareness (Meier, 2019; Voss et al., 2018). In the context of our paradigm this could mean that individuals with higher working memory capacity report more mind-wandering not because they are actually mind-wandering more, but rather are simply more aware of it.

This question of awareness of mind-wandering represents a broad limitation of the current study. If individuals are consistently "missing" mind-wandering, meaning that they start to mind-wander, then return to the task without reporting that mind-wandering happened, then

on-task durations could be incorrectly inflated, as the next time that mind-wandering is reported the previous on-task episode would include multiple episodes. One argument against this is that Figure 2.3, and a Shapiro-Wilk normality test show on-task durations to be largely normally distributed. If it was the case that entire mind-wandering episodes were consistently not being reported, one would expect a fairly salient right skew. Overall, we conclude it is unlikely that this limitation invalidates our other results.

Within-Individual Differences

Returning now to the question of which of our three proposed process models are most supported, we next turn to the within-individual lag analyses. While the individual-difference level most strongly supported an independent-process model, the within-individual level is logically independent and need not show the same result. The most prominent findings here were a positive lag-2 autocorrelation and an asymmetric negative lag-1 autocorrelation. Because episodes alternate types between on-task and mind-wandering, lag-1 durations refer to the length of the previous episode of the opposite type (on-task -> mind-wandering), whereas lag-2 durations refer to the length of the previous episode of the same type (on-task -> mind-wandering -> on-task). The positive lag-2 effect indicates that when an episode is longer, the next episode of the same type also tends to be longer, which is again consistent with separate underlying processes for on-task and mind-wandering durations. At the same time, the negative lag-1 effect from on-task to mind-wandering episodes indicates that when an on-task episode is longer, the next mind-wandering episode is shorter. r. Thus, the within-individual results again supported an independent-process model, but also revealed an additional competitive component between those two processes. This is important because it suggests that the clearest overall

pattern is still one of two separable processes, with only some competition emerging as an additional feature of how those processes interact over time.

The competitive process model was initially compared to resource control accounts of mind-wandering, where both on-task and mind-wandering episodes compete for a shared resource (Smallwood and Schooler, 2006, 2015; Thomson et al., 2015, 2018). However, this asymmetric lag-1 effect does not cleanly demonstrate that both on-task and mind-wandering episodes are competing for the same resource. Instead, this effect may more likely be reflecting a state of higher "focus" where individuals are able to stay on task longer, and catch themselves mind-wandering faster..

Also, on this within-individual level, our reward manipulation was unsuccessful, consistently exhibiting no significant effects. This was true when examining both average episode duration, and interactions with lag durations. While it is true that past research has also been relatively unsuccessful in finding reward effects on mind-wandering, the lack of such an effect is puzzling given the inherent role of cognitive-control in mind-wandering. In the present study we had hoped to resolve this by measuring both on-task and mind-wandering durations, theorizing that reward might only impact one of these two durations, and average to no effect when the two states are not measured separately. We also tested if the perceived importance of a given mind-wandering episode moderated the relationship between reward and mind-wandering, hypothesizing that there may be some kind of value balancing occurring, but found no significant effect.

In contrast to these value-based measures, the valence of mind-wandering episodes had several notable effects. First, when an episode topic was more positively valenced, the episode tended to last longer. Interestingly, the valence of upcoming mind-wandering episodes also had

an effect on the duration of the current on-task episode. We found a quadratic effect of valence such that more extremely valenced mind-wandering episodes (both positive and negative) resulted in shorter previous on-task episodes. More strongly, however, was a linear effect of valence such that on-task episodes were shorter when the upcoming mind-wandering episode was negatively valenced. This suggests that during a task, individuals may be occasionally buffeted by short off task thoughts, and in the case that these thoughts are more extremely (and particularly negatively) valenced, attention is more likely to swap to a full-blown mind-wandering episode. Thus, one possible explanation for the frequent failure of reward manipulations to influence mind-wandering is that the attentional dynamics governing mind-wandering may be driven more strongly by lower-level emotional valence than by higher-level value. A potentially fruitful future direction of mind-wandering research would be to test this hypothesis more directly.

Conclusion

The literature on mind-wandering has consistently debated whether mind-wandering represents cognitive control failure, or if mind-wandering itself competes for cognitive resources. Here, we relate these two conceptions of mind-wandering to an independent-process model, and an opponent process model. In an independent process model, mind-wandering and on-task focus are two separate, independent processes, while in an opponent process model the two states compete in some way. We found that at the individual-difference level, an independent-process model is best supported. At the within-individual level, the results again supported an independent-process model, but also revealed an additional, asymmetric, negative lag-1 component where longer on-task episodes were followed by shorter mind-wandering episodes.

.The clearest finding is thus that,mind-wandering and on-task focus are best understood as two separate processes, while we hypothesize that the asymmetric lag-1 effect is best described as a "focus" effect.

Limitations and Future Research

The most obvious limitation of the current work is that it is reliant on a new paradigm to measure mind-wandering onset. While we believe the eye-tracking results are a compelling validation of this paradigm, it is worth considering possible unforeseen confounds. For instance, our task is uniquely reliant on meta-awareness of attention, that is, on one's ability to adequately understand, and report where their attention currently is, and where it has been. Meta-awareness in general has not been studied nearly as extensively as mind-wandering, and so it is currently unclear to what degree individual difference in meta-awareness might reflect a limitation of the proposed paradigm. Future work might aim to replicate our findings across different tasks. We believe the overall structure of our paradigm can be creatively applied to other tasks. For example, breath counting is a common task used in mind-wandering research (Chu et al., 2023b; Levinson et al., 2012). Using a breath tracking device, researchers could obtain an objective time stamp of when each breath occurred. Participants would then report what number they lost track of counting at. This number would then be matched up to the time that the relevant breath occurred to obtain a timestamp of mind-wandering onset.

CHAPTER III

EEG TEMPORAL DYNAMICS ACROSS MIND-WANDERING: ONSET, MAINTENANCE, AND META-AWARENESS

Introduction

Mind-wandering, the shift of attention away from the external environment or current task toward internally generated thought, is often studied as though it were a single state that can be contrasted with on-task attention (Schooler et al., 2011, p. 20; Smallwood & Schooler, 2006, 2015). In experience, however, mind-wandering unfolds over time. Attention can drift gradually away from the task, remain off task for some period, and then begin to shift back toward the external environment before awareness of the lapse becomes explicit. That is, mind-wandering appears to have a temporal structure involving onset, maintenance, and cessation. Although past work has increasingly emphasized that mind-wandering unfolds over time rather than existing as a static state, the temporal profile of mind-wandering episodes themselves remains relatively unexplored, including both how the onset of an episode unfolds over time and whether transitions occur gradually or as discrete events (Christoff et al., 2016; Smallwood, 2013).

This question is especially relevant at the end of mind-wandering episodes, where meta-awareness is experienced as a discrete moment of realization (Schooler et al., 2011). Yet that subjective sense of a single moment does not by itself reveal how the transition out of mind-wandering unfolds. One possibility is that mind-wandering ends relatively discretely, with meta-awareness marking the point at which attention returns to the task. Another possibility is that the end of mind-wandering is gradual, such that attention begins shifting back toward the external

environment before awareness of the lapse becomes explicit. Here, meta-awareness would mark not the beginning of the transition out of mind-wandering, but the point at which an ongoing change in attentional state becomes reportable (Shinagawa et al., 2021, 2025).

These transitions are difficult to study using standard behavioral measures because they largely unfold covertly. The drift into mind-wandering often occurs without immediate conscious awareness, and even the return toward the task may begin before it becomes explicitly reportable through meta-awareness. This makes these attentional transitions difficult to study using standard behavioral measures. Methods that can track covert changes in attentional state over time are therefore especially useful in this context. EEG is well suited to this problem because it can capture such covert changes with a high degree of temporal precision. Indeed, EEG has already been informative regarding the neural correlates of mind-wandering, and a large literature has examined the extent to which mind-wandering is accompanied by reduced processing of external events and increased internally oriented attention (Kam et al., 2022; Smallwood et al., 2008). Yet despite mind-wandering involving inherently dynamic components, much of the EEG literature still collapses temporally distinct portions of the episode into a single “mind-wandering” category and a single “on-task” category. This makes it difficult to determine whether observed neural effects reflect the onset of the episode, its maintenance over time, or the transition out of it and into explicit meta-awareness (Christoff et al., 2016; Kam et al., 2022; Schooler et al., 2011; Smallwood & Schooler, 2015).

Despite this temporal ambiguity, research has consistently shown that mind-wandering is associated with reduced processing of external stimuli. Both empirical findings and theoretical accounts converge on the idea that mind-wandering involves a form of perceptual decoupling, in which attentional resources are withdrawn from the external task and redirected toward stimulus

independent, internal thought (Kam et al., 2022; Kam & Handy, 2013; Schooler et al., 2011, p. 20). ERP findings fit broadly within this account, with studies often reporting attenuated sensory and attentional responses during mind-wandering, suggesting weaker processing of external events while attention is disengaged from the environment (Kam et al., 2022; Smallwood et al., 2008). Related work has also shown that mind-wandering disrupts cortical phase-locking to perceptual events, again consistent with weaker coupling to ongoing sensory input (Baird et al., 2014). These findings suggest that one of the clearest conclusions from the EEG literature is that mind-wandering is marked by reduced engagement with the external environment.

Oscillatory findings point to a similar general pattern, though with somewhat greater variability across paradigm. Alpha power is among the most consistent oscillatory correlates of mind-wandering and is commonly interpreted as reflecting internally directed attention and reduced engagement with external sensory input (Arnau et al., 2020; Compton et al., 2019; Kam et al., 2022). More broadly, alpha has also been linked to the gating of external sensory information, consistent with the idea that alpha increases when attention is withdrawn from the environment and redirected inward (Ceh et al., 2020). Theta has likewise been implicated in mind-wandering, but its functional role has been less clear and its pattern less consistent across studies (Kam et al., 2022). In some cases, greater theta during mind-wandering has been discussed as part of a broader low-alertness or internally absorbed state, but the exact role of theta is largely still unclear (Aftanas & Golocheikine, 2001; Braboszcz & Delorme, 2011; Jin et al., 2019; Rodriguez-Larios et al., 2021). Outside of mind-wandering research, frontal-midline theta is more generally associated with conflict monitoring, uncertainty, and the recruitment of cognitive control, raising the possibility that theta-related effects during mind-wandering could partly reflect monitoring or reorientation processes rather than mind-wandering itself (Carter &

van Veen, 2007; Pscherer et al., 2020). Alpha and theta may therefore not simply provide two versions of the same signal. Rather, alpha may more directly reflect disengagement from the external environment, whereas theta may be especially informative about how the episode evolves and whether monitoring or control-related processes become increasingly relevant over time.

Here, the temporal dynamics of mind-wandering become especially theoretically informative. If theta primarily reflects processes that support internally engaged mind-wandering, it should increase closer to mind-wandering onset and remain elevated during sustained off-task thought (Aftanas & Golocheikine, 2001; Braboszcz & Delorme, 2011; Jin et al., 2019; Rodriguez-Larios et al., 2021). If instead theta partly reflects monitoring or control-related processes, it may become more prominent later in the episode, as participants begin to detect the lapse and attention starts to return toward the task (Cohen & Ridderinkhof, 2013; Nigbur et al., 2011; Pastötter et al., 2010, 2013; Pscherer et al., 2020; Trujillo & Allen, 2007). The mixed findings in the theta literature may therefore partly reflect the fact that different paradigms and analyses sample different temporal portions of the episode, but they may also suggest that theta does not behave in one consistent way across mind-wandering, instead reflecting different processes at different points in the episode.

Although the broader theoretical story of reduced external engagement is relatively coherent, how these signals change across a mind-wandering episode remains unclear. These temporal components are particularly relevant to the end of mind-wandering episodes. Meta-awareness of mind-wandering is experienced as a discrete event, but the end of mind-wandering episodes themselves need not be so discrete. In fact, recent work has begun to suggest that neural changes may emerge several seconds before awareness of mind-wandering is explicitly reported.

During a simple stimulus-response task, Shinagawa et al. (2021) found that P3 amplitude increased in the seconds before self-caught reports of mind-wandering, which they interpreted as evidence that attentional resources were returning to the task prior to explicit awareness. More recent work has likewise suggested pre-report changes in oscillatory and physiological measures during the transition from mind-wandering to awareness of its occurrence (Shinagawa et al., 2025). From this perspective, meta-awareness may not arise as an isolated event, but as the outcome of processes that build gradually as the episode unfolds.

Crucially, however, these studies examined neural changes relative only to reports of meta-awareness, not to mind-wandering onset (Shinagawa et al., 2021, 2025). Yet each time point within a mind-wandering episode also has important context relative to onset. For example, observed neural changes three seconds before meta-awareness could mean something very different for a five-second mind-wandering episode than for a ten-second episode. Without the broader temporal context of the full episode, it is difficult to determine whether apparent pre-report changes reflect the return toward task, shallow episodes, or even lingering variance associated with the drift into mind-wandering. Overall, it is clear that mind-wandering is not neurally identical to on-task attention but it remains unclear how those neural changes unfold across the temporal structure of an episode. This is especially important for understanding the end of mind-wandering episodes, where the central theoretical question is whether the return toward the task is better characterized as a relatively discrete event tied to meta-awareness or as a more gradual shift that begins earlier. In that sense, the time course of neural change may be particularly informative not only about how attention returns to the task, but also about the functional role of meta-awareness itself. At present, however, the literature does not clearly distinguish neural activity related to the onset of mind-wandering, its maintenance over time, and

the processes that unfold as the episode comes to an end. An important gap in the literature, therefore, is not simply whether mind-wandering differs from on-task attention, but how the episode unfolds over time and what that temporal structure reveals about the transition into and out of mind-wandering.

The Present Study

The present study was designed to address the question of how the temporal structure of mind-wandering unfolds, and in particular whether the end of a self-caught mind-wandering episode is better understood as a relatively discrete event tied to meta-awareness or as a more gradual return of attention toward the task. We do this by explicitly modeling the temporal anatomy of self-caught mind-wandering within the EEG signal. Participants listened to audiobook excerpts while maintaining fixation and were instructed to report mind-wandering whenever they noticed that it had occurred. Following each report, they identified the last point in the audiobook they remembered hearing before their attention drifted away. The presentation time of that selected text was used to estimate mind-wandering onset, while the self-caught report served as a marker of explicit meta-awareness. During listening, task-irrelevant colored dots were also presented intermittently to provide anchors for sensory ERP measurement (Courchesne et al., 1975; Debener et al., 2005). This combination of onset estimates, self-caught reports, and continuous EEG allowed us to move beyond a simple report-locked or state-based contrast and instead examine how neural activity changed across multiple portions of the episode. Because self-caught reports provide a measure of mind-wandering with meta-awareness, they are especially useful for examining the relationship between the ongoing episode and the moment at which it becomes explicitly reportable (Chu et al., 2023).

Our central aim was to characterize three broad phases of self-caught mind-wandering: the transition into mind-wandering, its maintenance over time, and the interval preceding meta-awareness. More broadly, the study sought to test whether neural activity observed before self-caught report is better understood as part of a discrete awareness event or as evidence that attention may begin to drift back toward the task several seconds earlier. If attention can gradually disengage from the external environment during the onset of mind-wandering, it may also gradually re-engage before participants explicitly notice that the episode has occurred. In this view, the button press marking self-caught meta-awareness would not represent the beginning of the transition out of mind-wandering, but rather the point at which an evolving change in attentional state becomes available to report.

Across neural measures, our predictions were guided by the broader idea that mind-wandering has a temporal structure, with potentially distinguishable phases of onset, maintenance, and pre-meta-awareness change. For spectral activity, we expected alpha power to increase as participants drifted off task and to remain elevated during sustained mind-wandering, consistent with prior work linking alpha to internally directed attention and reduced processing of external input (Arnau et al., 2020; Compton et al., 2019; Kam et al., 2022). Theta was likewise expected to increase during mind-wandering, although we also specifically considered the possibility that theta-related effects might become especially prominent closer to self-report if monitoring or control-related processes were recruited during the transition back toward the task (Cohen & Ridderinkhof, 2013; Nigbur et al., 2011; Pastötter et al., 2010, 2013; Pscherer et al., 2020; Trujillo & Allen, 2007). For the task-irrelevant colored dots, we expected sensory responses to be reduced during mind-wandering and to recover as attention shifted back toward the task, consistent with perceptual decoupling accounts (Kam et al., 2022; Smallwood et al.,

2008). Thus, the key questions are not simply whether neural activity differs between mind-wandering and on-task states, but when such differences emerge within an episode and what their timing reveals about the transition into mind-wandering, its maintenance over time, and the processes preceding meta-awareness. We preregistered our methods, predictions, and analyses: https://osf.io/kf7s8

Methods

Participants

Participants were recruited from the University of Oregon undergraduate participant pool and received course credit for participation. In addition, participants were eligible for performance-based monetary incentives tied to reading comprehension accuracy. Each experimental session lasted approximately 2.5 hr. We collected data from a total of 55 participants; 8 were excluded due to excessively noisy EEG, 14 were excluded due to experiment failures such as the amplifier battery dying mid experiment, computer lag destroying event code structure, or experimenter errors. After these exclusions, we used 33 participants (26 female, 7 male, mean age =19.60 years, SD = 3.59) for our analyses.

The target sample was 34 usable participants, with modest oversampling permitted if necessary to compensate for unusable EEG data. This target was guided by prior EEG studies of mind-wandering and by a proxy power analysis based on a medium effect size (d = .50, two-tailed, α = .05, power = .80), which indicated a required sample of 34 participants. Although the present time-segmented modeling approach is novel within this literature, this sample size exceeds the average sample size reported in a recent systematic review of electrophysiological markers of mind-wandering (Kam et al., 2022). The discrepancy between our target sample size

of 34 and our actual sample size of 33 came from the discovery of a bad subject after data collection had concluded.

Materials

The study used an EEG implementation of a self-caught mind-wandering paradigm during audiobook listening. Participants listened to excerpts from five audiobooks: *Walden* by Henry David Thoreau, *Crime and Punishment* by Fyodor Dostoevsky, *The Republic* by Plato, *Moby Dick* by Herman Melville, and *On the Origin of Species* by Charles Darwin. The order that the first four texts were delivered was counterbalanced across participants. The fifth text, *On the Origin of Species*, was always presented last and served only as a buffer text to hold the total experiment time constant regardless of the amount of mind-wandering reported (see *procedure* for details); data from this buffer text were not included in any analyses.

During audiobook listening, task-irrelevant colored dots were presented at fixation. Dots were red or blue, appeared at irregular intervals averaging approximately 1 Hz, and changed color on approximately 15% of presentations. Both dot onsets and color-change events included random temporal variability to reduce rhythmic expectancy effects.

After each mind-wandering episode participants responded to a short survey asking about the content of their mind-wandering. First, this survey asked about the type of mind-wandering (Robison et al., 2019). Here, the options were: “I was thinking about something related to the task”, “I was thinking about something unrelated to the current task”, “I was thinking about something in the environment”, and “I was zoned out, and not thinking about anything”. Next, using a 6-point Likert scale, participants indicated how pleasant or unpleasant the topic of their mind-wandering was. Finally, also using a 6-point Likert scale, participants indicate how

important or unimportant the topic of their mind-wandering was. For example, an important topic might be thinking about an upcoming test, while an unimportant topic might be thinking about a movie they saw last night.

After the audiobook task, participants completed a brief battery of cognitive-control tasks consisting of Stroop, Simon, and Flanker tasks. They then completed an individual-differences and demographics survey assessing trait mindfulness, ADHD-related symptoms, and meditation experience. Trait mindfulness was measured with the Mindful Attention Awareness Scale, ADHD symptoms with the Adult ADHD Self-Report Scale, and meditation history with three self-report questions assessing current practice, past consistent practice, and the longest period of sustained practice.

EEG data was collected using the Brain Products actiCap snap system consisting of 32 active Ag/AgCl electrodes fitted on an elastic cap in adherence with the international 10-20 configuration. HEOG was acquired through the placement of a single electrode adjacent to the right zygomatic bone and VEOG acquired by placing a single electrode on the left side of the maxilla below the left orbital. Each respectively provides information on horizontal and vertical eye movement. Electrode impedances were reduced to below 10 KOhms for recordings and were amplified using a Brain Product actiCHamp amplifier with a bandpass of 0.01- 100 Hz. The EEG was digitized at 1000 Hz. Preprocessing was conducted in MATLAB using EEGLAB and FieldTrip functions. For the spectral pipeline, the data were band-pass filtered from 1 to 40 Hz and then downsampled to 250 Hz prior to artifact handling and time-frequency decomposition. Raw EEG was referenced using the Fz channel and retained this reference for all subsequent preprocessing and analyses. EEG preprocessing and data export were conducted in MATLAB

2020b using FieldTrip 20240110, and EEGLab v13.6.5b (Delorme & Makeig, 2004; Oostenveld et al., 2011).

Procedure

After completing an informed consent form, participants' head circumference was measured to determine the appropriate EEG cap size. The experimenter then prepared the cap by attaching the electrodes, after which the cap was fitted to the participant's head and the electrodes were gelled to establish adequate contact. As electrode preparation neared completion, the experimenter delivered the task instructions. After confirming that electrode impedance was within an acceptable range, the task began.

Participants listened to audiobook excerpts while looking at a fixation cross on screen. During listening, participants were instructed to press the space bar as soon as they realized that their mind had wandered. This button press serves as a marker of meta-awareness of mind-wandering and as the end point of the mind-wandering episode (Schooler et al., 2011).

Following each meta-awareness report, the same audiobook passage was presented in text form on the screen. Participants scrolled through the text and identified the last point they remembered hearing before their attention drifted away from the text. Because the timing of the auditory presentation was known, this "last remembered text" provided an estimate of mind-wandering onset. Mind-wandering duration was therefore defined as the amount of time between the delivery of the last remembered text and the meta-awareness report. After each reported mind-wandering episode, participants completed a brief follow-up survey assessing the content of their thoughts, the subjective importance of the episode, and its emotional valence. The audiobook then resumed from the point the participant had identified as the last remembered text prior to the lapse in attention.

The experiment was structured around four main 10-min listening blocks. These blocks were defined in terms of listening time, such that timing was paused while participants completed the post–mind-wandering portion of the task. This ensured that for each text, participants were guaranteed to receive 10 minutes of listening time regardless of how much they mind-wandered.

A fifth audiobook excerpt, always *On the Origin of Species*, was presented only as a buffer text to hold the total experiment time constant. The duration of this text was reduced in correspondence with the amount of time spent on post mind-wandering surveys from the other blocks. This was done so that participants were not penalized with a longer experiment for reporting more mind-wandering. In the rare event that the overall time limit was reached before the four primary audiobook blocks had been completed, the experiment was extended until the end of the fourth primary block. Data from the buffer text were not analyzed.

After the participant completed listening to the audio books, EEG recording stopped, and they completed the reading comprehension questions, followed by the brief battery of cognitive-control tasks consisting of Stroop, Simon, and Flanker tasks, each lasting approximately 3 min. Finally, the demographics and individual difference survey was given before awarding the incentives from the reading comprehension questions.

Spectral Preprocessing

For the spectral analyses, continuous EEG data were first segmented into trials defined as the period of time from audio play to self-reports of mind-wandering, band-pass filtered from 1 to 40 Hz, and downsampled to 250 Hz. The resulting data were then visually inspected for large artifacts, and time segments containing such artifacts were marked for later exclusion. Artifact

handling distinguished between global and local contamination. Segments affecting the majority of channels were treated as global artifacts. Whole channels judged to be unusable after visual inspection were removed prior to subsequent processing. For local artifacts affecting fewer than 25% of channels, artifact times and channels were manually identified and then processed automatically: segments shorter than 2 s were repaired using piecewise cubic interpolation, whereas segments longer than 2 s were marked as artifactual. This approach was intended to preserve short, isolated signal disruptions while excluding longer periods likely to distort spectral estimates.

Criteria for excessive noise included persistent high-amplitude fluctuations, flat-line channels, and widespread artifact contamination. Entire trials were omitted if approximately 30% or more of the trial duration was contaminated by artifacts. Participants were excluded entirely if 40% or more of their trials were rejected due to excessive artifacts. These thresholds were chosen to account for the long duration of our trials (10–200 s), where some artifacts are expected. These criteria were treated as approximate guidelines for visual inspection rather than rigid cutoffs.

Two copies of the data were then created. In the first copy, artifactual time segments and channels were replaced with NAs. In the second copy, artifact times were marked but the data themselves were left intact. The first copy, with global artifacts replaced by missing values, was used for independent components analysis implemented with FieldTrip using the runica algorithm, estimating 20 components. Components identified through visual inspection as reflecting ocular activity were then removed from the second copy, which retained the original data values with artifacts only marked.

This second copy of the data was then transformed into the frequency domain using wavelet-based spectral decomposition. Power was estimated with a wavelet width of 7, retaining all trials and all time points. Theta power was quantified from 4-7 Hz within a frontal-midline ROI consisting of Fz, Cz, F3, F4, FC1, and FC2 (Cavanagh & Frank, 2014). Alpha power was quantified from 8-12 Hz within the following regions of interest (ROIs): a posterior ROI consisting of Pz, Oz, O1, and O2, and a second broader ROI consisting of P3, P4, CP1, CP2, Cz, F3, and F4 (Arnau et al., 2020; Baldwin et al., 2017; Compton et al., 2024; Thut et al., 2006). Only after time-frequency decomposition were the previously marked artifactual time segments and channels replaced with NAs. This removal was intentionally delayed until after decomposition to reduce boundary artifacts. Each ROI was then averaged into a single value per time point. If one channel within an ROI was replaced with NAs for a given period, the remaining channels were averaged.

Across included participants, a mean of 95.86% of channel-by-sample data points were retained after preprocessing (SD = 3.87, range = 85.84–99.94). Globally marked artifact periods accounted for a mean of 4.10% of time points (SD = 3.86, range = 0.06–14.16), whereas long local artifacts that were retained as missing data accounted for a mean of 1.21% of data points (SD = 3.97, range = 0.00–21.33). Short local artifact interpolation was negligible in the final dataset (M = 0.00%, SD = 0.00, range = 0.00–0.01).

Prior to model fitting, spectral power estimates were averaged within temporal bins. This binning step was used to reduce the density of highly autocorrelated EEG time points and thereby lessen the risk of overstating statistical precision from very finely sampled temporal data (Lazic, 2010; Mitchell et al., 2019). The primary models used 40 Hz temporal binning, which provided a compromise between limiting oversampling and preserving sensitivity to relatively

brief within-episode changes, particularly in the period preceding meta-awareness. Because the degree of temporal averaging could influence sensitivity to transient effects, we also repeated the main spectral models at 25 Hz and 10 Hz as sensitivity analyses.

ERP Preprocessing

For ERP analyses, EEG data were band-pass filtered from 0.1 to 40 Hz. The continuous data were then epoched around the onset of each dot stimulus using a window from -200 to 1,000 ms relative to stimulus onset, and baseline corrected using the -200 to 0 ms pre-stimulus interval. Artifact rejection was performed at the epoch level, such that contaminated epochs were removed entirely rather than repaired. This removal focused primarily on ocular artifacts, as well as other large sources of noise likely to distort ERP estimates. Specifically, peak-to-peak voltage was computed within an artifact-detection window spanning -200 to 600 ms for both a blink-sensitive channel and a horizontal eye-movement channel. Epochs were flagged as artifactual if peak-to-peak amplitude exceeded 150 μV in the blink channel or 75 μV in the horizontal eye-movement channel. Epochs identified as artifactual were then excluded from further ERP estimation by replacing the full epoch with missing values. This approach was chosen because, unlike the spectral analyses, the ERP analyses depended on clean trial-locked averages, making it preferable to remove contaminated epochs entirely rather than interpolate or partially retain them. Across included participants, a mean of 45.14% of epochs were rejected (SD = 21.47, range = 9.31–95.28), corresponding to a mean retention rate of 54.86% of dot-locked epochs (SD = 21.47, range = 4.72–90.69).

After artifact rejection, ERP amplitudes were quantified separately for the preregistered P1, N1, N2, and P3 components. Mean amplitude was extracted within fixed time windows for

each component: 80-120 ms for P1, 120-180 ms for N1, 200-350 ms for N2, and 300-600 ms for P3. These amplitudes were computed within predefined electrode ROIs. P1 and N1 were measured from occipital electrodes O1, Oz, and O2; N2 was measured from Fz and Cz; and P3 was measured from Cz and Pz (Folstein & Van Petten, 2008; Hillyard & Anllo-Vento, 1998; Polich, 2007). Within each epoch, voltage was first averaged across the electrodes in the relevant ROI and across all time points in the relevant component window, yielding a single value per component per epoch.

Time-segmented modeling strategy

All of our analyses used time-segmented multi-level regression to characterize electrophysiological change across different phases of mind-wandering. The following modeling strategy was repeated for each spectral and ERP measure as the outcome variable. This modeling approach was motivated by the fact that mind-wandering episodes vary substantially in their onset times, durations, and offsets, making simple event-locking strategies insufficient for capturing the full temporal anatomy of an episode. The segmented approach therefore modeled the drift into mind-wandering, the period during which it was maintained, and the interval preceding meta-awareness separately. Several time-varying predictors were defined accordingly.

$$\begin{aligned}\mathrm{EEGMeasure}_{ijk} = {} & \beta_0 + \beta_1\,\mathrm{TimeUntilMW}_{ijk} + \beta_2\,\mathrm{MWMaintenance}_{ijk} \\ & + \beta_3\,\mathrm{MAInterval}_{ijk} + \beta_4\,\mathrm{MWStep}_{ijk} + \beta_5\,\mathrm{MAStep}_{ijk} \\ & + b_{0k}^{(\mathrm{Subject})} + b_{0jk}^{(\mathrm{Episode})} + \varepsilon_{ijk}\end{aligned}$$

TimeUntilMW modeled linear change during on-task periods as a function of time remaining until mind-wandering onset and was coded as 0 following

onset. *MWMaintenance* was coded as 0 before mind-wandering onset, increased linearly during the episode itself, and was reset to 0 beginning 4 s before the meta-awareness report. *TimeUntilMA* modeled linear change within mind-wandering episodes as a function of time remaining until meta-awareness. Several step-function predictors were also defined: *MWStep*, which switched from 0 to 1 at mind-wandering onset, and *MAStep,* which switched from 0 to 1 beginning 4 s before the meta-awareness report. To more precisely test the timing of meta-awareness-related changes, a second set of preregistered models expanded on the above equation by splitting *MAStep* with two separate step terms: *MAStep4*, beginning 4 s before meta-awareness, and *MAStep1.5*, beginning 1.5 s before meta-awareness. These models were intended to distinguish earlier from later changes preceding the report of meta-awareness. Lastly, we included subject and episode number as random intercepts. *Episode* here refers to the pair of one on-task episode and the following mind-wandering episode.

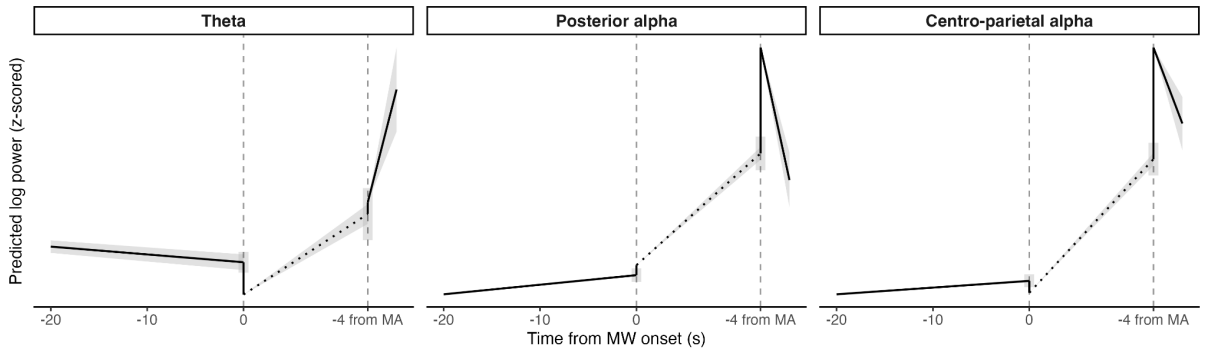
Our pre-registration specified that maximal models including all random slopes would first be tested, and only be reduced to fixed effect only models following convergence issues. Across all the below results, these maximal models failed to converge. We next attempted to run separate models where each predictor was included as a random effect. These models also failed to converge, therefore the reported results come from a model included no random slopes. Our pre-registration also prescribed using a "*Total experiment time"* variable to track the total elapsed time since experiment onset in seconds and was intended to capture gradual changes over the course of the task, such as fatigue or general mental drift. We opted to exclude this variable from our main models, instead allowing the random intercept of *Episode* number to capture this across experiment variance without diluting the within episode effects.

Results

Spectral Analyses

Preregistered spectral models were used to characterize EEG dynamics across three main phases of the mind-wandering episode: the transition into mind-wandering, the maintenance of mind-wandering, and the period preceding self-caught meta-awareness. We first examined full piecewise models containing both gradual and step-like terms, and then examined timing-focused models that compared model fits for pre-meta-awareness related changes from -5.5s to -1.5s.

Figure 3.1 Predicted Neural Dynamics for an Average Mind-Wandering Episode



Transition into Mind-Wandering

The transition into mind-wandering was reflected most clearly in the continuous time term leading up to mind-wandering onset. Consistent with our pre-registered predictions, as participants approached mind-wandering onset, theta and both alpha ROIs increased (Table 1). The step term at mind-wandering onset was statistically significant for theta, where the step term was negative, as well as for both alpha ROIs, but in inconsistent directions. These specific results should be interpreted cautiously, these step terms involve only a single transition point, meaning

that observed small betas are small effects. Given their small magnitude and inconsistent direction across bands, the MW step effects themselves do not provide clear support for the preregistered prediction of onset related effects. This suggests that the drift into mind-wandering may unfolded gradually rather than appearing as a purely abrupt shift at onset.

Mind-Wandering Maintenance

Consistent with our preregistered predictions, the mind-wandering maintenance term indicated sustained spectral differences during the mind-wandering period. Theta increased across the maintenance interval, and alpha likewise increased across both ROIs (Table 1). These results are consistent with our pre-registration where we predicted spectral measures would change as individuals drifted into, and maintained mind-wandering.

Table 3.1. Segmented Regression Model Results Across Theta and Alpha

Segmented mixed-effects models predicting spectral power

	Theta				**Alpha ROI1**				**Alpha ROI2**			
Predictors	*b*	*std. Error*	*t*	*p*	*b*	*std. Error*	*t*	*p*	*b*	*std. Error*	*t*	*p*
(Intercept)	6.168	0.094	65.693	**<0.001**	6.544	0.165	39.687	**<0.001**	6.328	0.153	41.404	**<0.001**
Time until MW onset	-0.000	0.000	-7.857	**<0.001**	0.001	0.000	51.612	**<0.001**	0.001	0.000	47.591	**<0.001**
MW maintenance	0.000	0.000	2.271	**0.023**	0.003	0.000	14.236	**<0.001**	0.003	0.000	16.137	**<0.001**
Time until meta-awareness	0.007	0.003	2.794	**0.005**	-0.025	0.004	-6.023	**<0.001**	-0.017	0.004	-4.654	**<0.001**
MW step	-0.012	0.002	-6.103	**<0.001**	0.007	0.003	2.466	**0.014**	-0.002	0.003	-0.633	0.527
Meta-awareness step	-0.008	0.005	-1.754	0.079	0.026	0.007	3.528	**<0.001**	0.028	0.007	4.213	**<0.001**
Marginal R^2 / Conditional R^2	0.000 / 0.457				0.004 / 0.518				0.003 / 0.543			

Period Preceding Meta-Awareness

The preregistration predicted different patterns for alpha and theta in the period preceding self-caught meta-awareness. Theta was expected to show a brief event-related increase before report, whereas alpha was expected to decrease toward on-task levels. In both alpha ROIs there was a significant positive step term at the -4 second mark, however moving from this point

onward toward meta-awareness was associated with a significant decrease in alpha (Table 1). This is consistent with a return away from the elevated mind-wandering pattern as meta-awareness approached. By contrast, theta showed a reliable ramping in the preceding seconds before meta-awareness but no evidence of a discrete early step (Table 1).

Because the primary time-segmented spectral models relied on temporally binned power estimates, we also examined the robustness of these findings across alternative bin widths. The alpha findings were generally stable across resolutions, remaining significant even at a bin size of 10 Hz. The theta findings were more sensitive to temporal resolution: although the key theta effects remained directionally consistent at 25 Hz and 10 Hz, they were attenuated at the coarser bin widths, with the maintenance effect no longer significant at 25 Hz or 10 Hz and the pre-meta-awareness theta slope no longer statistically reliable at 10 Hz. This suggests that the theta effect was more temporally focal, and therefore more vulnerable to smoothing from temporal averaging, than the alpha effects. We next turned to the competing-onset analyses, which did not rely on temporal binning, to further localize the timing of pre-meta-awareness spectral changes.

To more precisely localize neural changes preceding meta-awareness, our preregistration specified comparisons between two candidate change points, at -4 s and -1.5 s relative to meta-awareness. However, we deviated from this plan in favor of a competing-onset approach, which we judged to provide a more robust assessment of when pre-meta-awareness changes began than an analysis limited to only two, relatively arbitrarily defined, candidate windows. Toward this end, we focused on the final 6 seconds of mind-wandering episodes and modeled log power as a function of time since mind-wandering onset interacting with total episode duration, along with candidate step and ramp terms. The step term captured an immediate shift at the onset specified by a given model, whereas the ramp term captured the subsequent linear change from that onset

toward meta-awareness. Separate model sets were fit for each alpha ROI and for theta, with candidate onsets ranging from -5.5 to -1.5 s relative to meta-awareness in 0.5 s increments. To help reduce the influence of pre-response motor activity, the final 1 second before report was again removed from these analyses. Overall, this approach allowed us to test which candidate onset best accounted for pre-report neural changes, thereby providing a data-driven estimate of when these changes most likely began before meta-awareness.

Across competing-onset models, the timing of report-locked spectral changes differed between alpha and theta. For alpha, the best-fitting models localized the onset of the pre-report change to approximately 3.0 s before meta-awareness. In ROI1, the best-fitting model placed the onset at -3.0 s and showed a significant negative step term ($b = -0.073$, $SE = 0.006$, $t = -12.9$, $p < .001$) followed by a significant negative ramp term ($b = -0.022$, $SE = 0.003$, $t = -6.75$, $p < .001$). In ROI2, the best-fitting model placed the onset at -3.0 s and likewise showed a significant negative step term ($b = -0.060$, $SE = 0.005$, $t = -12.5$, $p < .001$) and a significant negative ramp term ($b = -0.020$, $SE = 0.003$, $t = -7.24$, $p < .001$). In both ROIs, the -3.0 s onset model was clearly preferred over the next-best competing-onset model at -3.5 s, with $\Delta AIC = 19.37$ for ROI1 and $\Delta AIC = 81.77$ for ROI2. Because alpha was hypothesized to reflect a gradual return toward task, we also compared slope-only and step+ramp versions of the competing-onset models. In both alpha ROIs, the step+ramp model fit better than the slope-only model, indicating that the pre-report alpha effect was better characterized as a downward shift followed by continued decline rather than as a purely gradual ramp. Overall, this suggests that in both alpha ROIs, the pre-report alpha change began approximately 3.0s before meta-awareness and continued to decline from there.

Theta showed a slightly later best-fitting onset. The winning theta model placed the onset at -2.5 s relative to meta-awareness, outperforming the next-best -2.0 s model by $\Delta AIC = 6.32$, with all earlier candidate onsets showing substantially worse fit (all $\Delta AICs \geq 28.3$ for onsets at -3.0 s or earlier). Unlike alpha, however, theta was not best described by a simple monotonic ramp. Instead, the best-fitting theta model was characterized by a significant positive step ($b = 0.017$, $SE = 0.004$, $t = 4.83$, $p < .001$) followed by a significant negative ramp ($b = -0.031$, $SE = 0.002$, $t = -14.1$, $p < .001$). Thus, theta was best localized to a later pre-report window beginning around 2.5 s before meta-awareness, but the shape of the effect was better characterized as a brief asymmetric event-like change than as a sustained linear increase.

Because the pre-registration described frontal theta as a brief event-related increase, we also tested whether a transient triangular-bump model would better characterize the theta effect. The best-fitting triangular model was centered at -2.0 s and spanned approximately -3.0 to -1.0 s, with a positive bump coefficient ($b = 0.038$, $SE = 0.003$, $t = 11.70$, $p < .001$). However, this model fit substantially worse than the best-fitting theta step+ramp model in a direct comparison ($\Delta AIC = 59.6$). Thus, although theta was clearly concentrated in the final few seconds before meta-awareness, its temporal profile was not well captured by a simple symmetric burst. Instead, it was better characterized by an asymmetric late event consisting of a positive shift followed by decline.

These late pre-report effects could in principle reflect motor-response preparation rather than neural changes related to meta-awareness itself, we re-ran the winning alpha and theta step+ramp models while excluding the final 1.0, 1.5, and 2.0 s before report. For alpha, the same overall pattern remained across exclusion windows in both ROIs: the step term stayed negative in both regions, and the ramp term also remained negative in ROI1 across exclusion windows

and in ROI2 at 1.0 s exclusion. In ROI1, the ramp remained significant even with the most conservative 2.0 s exclusion (b = -0.099, SE = 0.007, t = -14.7, p < .001). In ROI2, the ramp was strongest with 1.0 s exclusion (b = -0.02, SE = 0.00401, t = -5.78, p < .001) and was reduced and no longer significant at 1.5 s (p = .622) and 2.0 s (p = .417). The negative alpha step remained significant across all exclusion windows in ROI2, including 2.0 s (b = -0.069, SE = 0.006, t = -10.7, p < .001) whereas in ROI1 the step term was reduced and no longer significant at 2.0 s (p = .075).

For theta, the same basic asymmetric pattern remained at 1.0 and 1.5 s exclusion, with a significant positive step at 1.0 s (b = 0.019, SE = 0.004, t = 4.82, p < .001) and 1.5 s (b = 0.017, SE = 0.005, t = 3.68, p < .001) followed by a significant negative ramp at 1.0 s (b = -0.034, SE = 0.004, t = -8.39, p < .001) and 1.5 s (b = -0.028, SE = 0.007, t = -3.94, p < .001). With 2.0 s exclusion, the positive theta step remained significant (b = 0.014, SE = 0.006, t = 2.31, p = .021) whereas the ramp term was reduced and no longer significant (p = .468). These sensitivity analyses suggest that the observed alpha and theta effects were not driven solely by motor related activity immediately surrounding the button press.

ERP Analyses

ERP analyses provided little clear evidence for systematic modulation of task-irrelevant dot-evoked responses across the mind-wandering episode. During the transition into mind-wandering and its maintenance, preregistered predictors were not reliable for any component (all $ps \geq .170$). Some effects emerged in the broader 4 s pre-meta-awareness window: P1 (b = 3.66, SE = 1.49, t = 2.45, p = .014), N1 (b = 3.24, SE = 1.47, t = 2.21, p = .027), N2 (b = 2.65, SE = 1.14, t = 2.32, p = .020), and P3 (b = 3.13, SE = 1.23, t = 2.55, p = .011), whereas the

corresponding Time-until-MA slopes were not reliable (all *ps* ≥ .064). Because this pattern was broadly positive across components, including those that are canonically negative-going, and because visual inspection of the waveforms suggested a general voltage shift rather than clear component-specific modulation, we do not make strong claims about ERP dynamics preceding meta-awareness.

Results Summary

Overall, the preregistered spectral analyses provided the clearest evidence for temporally structured neural changes across mind-wandering episodes. Theta and alpha both changed as participants approached mind-wandering onset and remained altered during the maintenance period, indicating that the transition into mind-wandering was gradual and sustained rather than instantaneous. In the period preceding meta-awareness, alpha was characterized by an earlier pre-report decline, with follow-up competing-onset analyses localizing this change to a window beginning approximately 3-3.5s before self-report. By contrast, theta was characterized by a later pre-meta-awareness effect, with follow-up analyses localizing this change to approximately 2.5 s before self-report. Importantly, this late theta effect was not best described as a simple ramp or symmetric burst, but rather as a brief asymmetric event-like change consisting of a positive shift followed by decline. ERP results were less clear: although some differences emerged in the broader pre-report window, they were difficult to interpret and did not support strong claims about ERP mind-wandering temporal dynamics.

Discussion

The present study examined how the temporal structure of self-caught mind-wandering unfolds by modeling neural activity relative to both estimated mind-wandering onset and explicit meta-awareness reports. More specifically, we examined self-caught mind-wandering as a temporally structured episode involving phases of onset, maintenance, and ending, with particular interest in whether the end of an episode is better characterized as a relatively discrete event tied to meta-awareness or as a more gradual return of attention toward the task. The clearest findings came from the spectral analyses. Across the episode, both alpha and theta changed as participants approached mind-wandering onset, suggesting that the transition into mind-wandering was gradual rather than instantaneous. During mind-wandering itself, alpha remained elevated, consistent with the idea that the internally oriented state was sustained over the course of the episode. In the period preceding meta-awareness, however, alpha and theta diverged. Alpha began to decline several seconds before self-report, whereas theta showed a slightly later pre-report effect concentrated closer to the report itself. These findings suggest that self-caught mind-wandering is not best understood as a single discrete neural event. Rather, the end of a mind-wandering episode may involve multiple overlapping processes that unfold over time, with some aspects of attention beginning to return toward the task before meta-awareness becomes explicitly reportable.

The alpha findings provide the clearest support for this interpretation. Across both ROIs, alpha increased as participants approached mind-wandering onset and remained elevated during the maintenance period, consistent with prior work linking alpha to internally directed attention and reduced processing of external input (Arnau et al., 2020; Compton et al., 2019; Kam et al., 2022). Critically, alpha did not remain elevated all the way to self-report. Instead, it began to

decline prior to meta-awareness, suggesting that the neural state associated with mind-wandering had already started to shift back toward on-task levels before participants explicitly noticed the lapse (Shinagawa et al., 2021, 2025). Follow-up competing-onset analyses localized this pre-report alpha change to roughly 3 s before meta-awareness, and related shape analyses suggested a closely similar window of approximately 3 to 3.5 s across the two ROIs. Thus, although the exact best-fitting onset varied somewhat across analyses, the broader pattern was consistent: alpha began reversing several seconds before the report of meta-awareness.

Meta-awareness may not itself mark the beginning of the return to task. Instead, one possibility is that meta-awareness reflects a response to an earlier attentional shift back to the environment that had already occurred. Another is that, just as attention may drift gradually into mind-wandering, it may also drift gradually out of it, with meta-awareness marking the point at which that gradual attentional shift becomes explicit enough to report (Henríquez et al., 2016; Mittner et al., 2016). The present data do not allow these possibilities to be distinguished definitively. However, they do strongly suggest that the offset of mind-wandering in some way begins before the moment that participants become consciously aware of it.

Theta showed a different temporal profile. Like alpha, theta changed as participants approached mind-wandering onset, indicating that it too tracked the transition into the episode. However, the later portion of the episode looked different for theta than for alpha. Rather than showing an early return toward on-task baseline, theta exhibited a somewhat later pre-report effect concentrated closer to meta-awareness. Competing-onset analyses localized this effect to approximately 2.5 s before self-report, and follow-up model comparisons indicated that it was not best described as either a simple monotonic ramp or a symmetric burst. Instead, the best-fitting account was an asymmetric late event consisting of a positive shift followed by decline.

This is notable because our preregistration predicted that frontal theta would show a brief event-related increase before self-report if meta-awareness recruited conflict-monitoring or control-related processes, rather than simply reflecting a gradual return to baseline.

Event-related increases in frontal-midline theta have often been linked to conflict monitoring, uncertainty, and the recruitment of cognitive control, with medial frontal systems including anterior cingulate cortex often implicated in these processes (Botvinick et al., 2001, 2004; Carter & van Veen, 2007; Cohen & Ridderinkhof, 2013; Nigbur et al., 2011; Pastötter et al., 2010, 2013; Pscherer et al., 2020; Trujillo & Allen, 2007). Viewed from that perspective, the shape of the theta effect may be theoretically informative. If theta were simply tracking the same sustained disengagement reflected in alpha, one might have expected a broader continuation of the ongoing episode-level pattern, or gradual return to baseline. Instead, the best-fitting theta model suggested a relatively brief, asymmetric event, which is theoretically consistent with the emergence of a monitoring- or control-related signal as participants moved closer to explicit awareness of the lapse (Muralidharan et al., 2023). One possible interpretation is that theta partly reflected processes involved in monitoring and detecting a mismatch between ongoing thought and current task goals and in mobilizing a return to task (Sandved-Smith et al., 2021). However, this interpretation is speculative, and the present data do not establish that the theta effect specifically reflects conflict monitoring. At minimum, the findings suggest that theta may have become especially relevant during the later portion of the episode, closer to explicit report, rather than simply mirroring the broader alpha pattern throughout.

The late timing of this theta effect may also clarify how mind-wandering duration could be partly governed by processes other than those that sustain on-task attention. In Chapter 2, on-task and mind-wandering durations were best described as separable latent processes, suggesting

that individual differences in remaining on task are not identical to individual differences in how long mind-wandering episodes persist. The present findings provide a possible neural complement to that behavioral dissociation: rather than showing only a gradual recovery of sustained attention, theta emerged near the end of mind-wandering episodes, consistent with a distinct control-related process that may help determine when an episode terminates.

More broadly, this interpretation may also help contextualize the mixed theta literature on mind-wandering. Compared with alpha, theta findings have generally been much less consistent and have often been interpreted either as reflecting task disengagement or low alertness (Aftanas & Golocheikine, 2001; Braboszcz & Delorme, 2011; Jin et al., 2019; Rodriguez-Larios et al., 2021). The present results fit only partially with the former view. Theta did change as participants approached mind-wandering onset, suggesting that it was not exclusively tied to meta-awareness. However, the later pre-report effect was relatively focal and event-like, which is somewhat more consistent with the idea that frontal theta becomes especially relevant as monitoring or control-related processes emerge closer to explicit report (Muralidharan et al., 2023). It is therefore possible that mixed findings in the theta mind-wandering literature partly reflect temporal heterogeneity within episodes, such that different studies may be capturing different phases of theta dynamics rather than a single uniform process.

Overall, the dissociation between alpha and theta suggests that the end of a mind-wandering episode may involve at least two partially dissociable processes: an earlier reduction in the internally oriented state itself, reflected more clearly in alpha, and a later theta-related change that cannot yet be clearly attributed to any specific underlying process.

The ERP findings were much less clear. There was little evidence for robust ERP modulation across mind-wandering onset or maintenance, and the pre-meta-awareness ERP

effects that did emerge were difficult to interpret confidently. Although several components showed effects in the broader pre-report window, these effects were positive across components, including components that are canonically negative-going, and visual inspection suggested a more general voltage shift rather than clean component-specific modulation. For this reason, we do not make strong claims about ERP temporal dynamics in the present data. One likely reason for the discrepancy between the spectral and ERP findings is that the ERP probes were task-irrelevant colored dots, which may have provided a relatively insensitive measure of the subtle attentional changes unfolding across these long and variable episodes.

Limitations and Future Directions

One limitation of the present study is that the data were relatively noisy, particularly given the long and variable duration of the analyzed episodes. The interval from task onset to meta-awareness often spanned many seconds or even minutes, yet these extended intervals could not be simply averaged in the way more conventional EEG designs often allow, because the temporal structure of each episode differed. This made it more difficult to characterize within-episode change cleanly and likely contributed to the weaker or less stable effects in some analyses. A related limitation is that some aspects of the spectral results were sensitive to temporal binning. Although the alpha findings were generally robust across bin widths, theta was more affected by temporal smoothing, with later within-episode effects becoming less consistent at coarser resolutions. This does not undermine the main theta result, but it does suggest that the late theta effect may have been relatively temporally focal or less stable and should be interpreted with appropriate caution. More broadly, because spectral markers of mind-wandering can vary across tasks, it remains unclear how fully the present results would generalize beyond

this audiobook-listening paradigm (Compton et al., 2024). Future work could test whether similar temporal dynamics emerge in other tasks and whether the late theta effect can be more directly linked to monitoring, control, or meta-awareness-related computations.

Conclusion

The present findings support a more temporally structured view of self-caught mind-wandering. The transition into mind-wandering appears to involve gradual spectral change rather than an abrupt switch, and the end of the episode may likewise unfold over multiple seconds. In particular, the alpha results suggest that the return toward task may begin several seconds before explicit meta-awareness, whereas the theta results suggest that later-emerging processes may continue building closer to the moment of report. We conclude that meta-awareness may not be best understood as a purely instantaneous event, but instead as the culmination of a gradual transition.

CHAPTER IV

GENERAL DISCUSSION

Mind-wandering is often studied as a contrast between being on task and being off task (Schooler et al., 2011; Smallwood & Schooler, 2006). The central aim of this dissertation was to move beyond that framing and instead recognize that mind-wandering is something that inherently unfolds over time. During everyday life, attention moves back and forth between periods of task focus and periods of mind-wandering, and the broader argument of this dissertation is that the temporal structure of this ebb and flow is itself informative about the cognitive structures that support both states. Across the three present studies, temporal structure became visible at two scales: within individual mind-wandering episodes, which showed a meaningful internal anatomy, and across sequential on-task and mind-wandering periods, which showed systematic structure in how they related to one another over time. The common conclusion is that the temporal dynamics of mind-wandering are critical for understanding the phenomenon itself.

This dissertation makes three main contributions to the literature. First, it introduces a new method for approximating mind-wandering onset. A major obstacle in the mind-wandering literature is that most existing methods do not provide an estimate of when mind-wandering begins (Chu et al., 2023; Smallwood, 2013; Smallwood & Schooler, 2015). Without an onset measure, it is difficult to examine episode duration, transitions into and out of mind-wandering, or the relationship between successive on-task and off-task periods. The audiobook paradigm developed here was intended to address that problem by using the last remembered text as a behavioral estimate of onset. This makes it possible to approximate onset much more directly

than what has historically been possible, and more importantly it makes temporal questions about mind-wandering directly testable. That methodological advance, in turn, made the second major contribution possible: showing that on-task and mind-wandering episode durations are not best understood as either uni-directional, or opposite expressions of a single shared process, but instead reflect largely separable, underlying processes. It also made the third contribution possible by allowing the end of a self-caught mind-wandering episode to be studied in relation to its onset and overall temporal structure, rather than only in relation to the moment of report. Here I found that the transition into meta-awareness is not limited to the moment of report, but may begin several seconds earlier, with neural changes emerging before participants explicitly report catching themselves mind-wandering. Together, these findings argue for a more temporally structured account of mind-wandering than is typical in the literature.

Within-Episode Temporal Dynamics

The first level of temporal structure that became possible to examine with this method was the internal anatomy of a single mind-wandering episode. Across the eye-tracking and EEG studies, meaningful changes emerged at the beginning of the episode, during its maintenance, and again in the period leading up to meta-awareness. In the eye-tracking data, pupil size and fixation duration changed systematically across the episode, including in the final seconds before participants reported catching themselves mind-wandering. In the EEG data, alpha and theta also changed as participants approached mind-wandering onset, remained altered during maintenance, and then showed distinct patterns near the end of the episode. Thus, it appears that a self-caught mind-wandering episode has measurable internal structure: attention drifts away from the task, mind-wandering is maintained for some period, and then the episode begins to shift again before meta-awareness becomes explicitly reportable.

The period preceding meta-awareness was especially informative in this regard. Although meta-awareness is experienced and reported as a discrete event, the present findings suggest that the transition into meta-awareness is not confined to the moment of report itself (Schooler, 2002; Schooler et al., 2011). In the EEG data, alpha began to reverse back toward on-task levels earlier, whereas theta showed a later, more spike-like effect concentrated closer to self-report. In the eye-tracking data, both pupil size and fixation duration also changed in the final seconds before meta-awareness. Across two very different measurement modalities, these findings suggest that the meta-awareness of mind-wandering episode is not best understood as a single discrete event. Rather, changes associated with the transition out of mind-wandering appear to emerge several seconds before meta-awareness becomes explicitly reportable (Shinagawa et al., 2021, 2025).

While alpha and the eye-tracking measures appeared to drift back toward on-task patterns in the seconds preceding meta-awareness, theta showed a different temporal profile. Rather than an early return, the theta effect emerged later, was concentrated closer to self-report, and was better captured by a brief spike-like change rather than by a gradual ramp. This suggests that theta may have been tracking something different from the earlier return-to-task pattern reflected in alpha and the eye measures. In the broader cognitive control literature, frontal-midline theta is often linked to conflict monitoring and the recruitment of control (Botvinick et al., 2001, 2004; Carter & van Veen, 2007; Pscherer et al., 2020). I hypothesize that a similar conflict monitoring process may help cue awareness of mind-wandering. As attention shifts back toward the task, the mismatch between ongoing thought and current goals may become increasingly salient, eventually contributing to the explicit realization that one has been mind-wandering. The present data do not establish that interpretation directly, but the later timing and spike-like shape of the theta effect are at least compatible with it.

Whatever the specific mechanisms involved, the eye-tracking and EEG findings converged on the same temporal claim. In both cases, a mind-wandering episode showed meaningful internal change across time, including in the period preceding meta-awareness. That convergence makes it harder to treat mind-wandering as a uniform off-task state. Instead, it points to the episode dynamics itself as an informative unit of analysis. Once the episode is treated that way, the next question is how episodes are organized beyond the single-event level—specifically, how periods of mind-wandering and on-task focus alternate and constrain one another over time.

Across-Episode Temporal Dynamics

Chapter 2 addressed that larger-scale temporal question by examining the structure of multiple episodes rather than the internal anatomy of a single one, and testing three candidate models; a single process model where the duration of mind-wandering and on-task periods are dependent upon a single underlying factor, an independent process model, where two unique underlying processes contribute towards episode durations, and finally a competing process model, where some shared resources is being competed for.

At the between-person level, on-task and mind-wandering durations were best described as fully independent latent processes, rather than as uni-directional or opposite expressions of a single shared factor. This is important because it suggests that mind-wandering is not simply the opposite of on-task focus. This pattern is generally consistent with executive-failure style accounts, such as McVay and Kane's (2009, 2010, 2012) view, in which control failures help explain why mind-wandering occurs, but the duration of mind-wandering is not governed by the same process that sustains on-task focus. Although importantly I did not specifically test for

cognitive control failures being the cause of mind-wandering here. Rather, the consistency with control failure accounts of mind-wandering is purely structural. The EEG findings further support this two-factor account because the theta effect was especially salient at the end of mind-wandering episodes. If mind-wandering duration were simply the inverse of the process that sustains on-task focus, then the return from mind-wandering should primarily reflect the recovery of that same sustained-attention process; instead, the late theta effect suggests that a distinct control-related process may help determine when mind-wandering episodes end. In terms of previous work, this pattern also fits reasonably well with frameworks like Mittner et al.'s (2016) tripartite model, which likewise treat on-task and mind-wandering states as supported by largely separable systems.

At the within-person level, the picture looked largely the same, despite the between-individual and within individual levels of analyses being logically independent, and thus not necessarily requiring convergent results. t. The lag analyses again showed the most support for an independent-process model, but an additional asymmetric lag-1 component such that longer on-task episodes were followed by shorter mind-wandering episodes. . Overall, I found little support for resource control accounts of mind-wandering where on-task and mind-wandering episodes compete for a shared resource (Smallwood and Schooler, 2006, 2015; Thomson et al.'s, 2015). In contrast to this, my results are more consistent with cognitive control failure accounts of mind-wandering which propose that mind-wandering occurs due to cognitive control failures, but don't say much as to what causes mind-wandering to end, thereby implying multiple processes are involved. This is perhaps the most theoretically important contribution of the dissertation. The clearest overall pattern was evidence for two separable processes underlying on-task and mind-wandering durations. The broader implication is that mind-wandering should

not be studied as a single, unitary construct. Instead, theories of mind-wandering need to distinguish among the processes that sustain task focus, the processes that allow mind-wandering to persist, and the processes that return attention to the task. The mechanisms that give rise to mind-wandering may differ from the mechanisms that sustain it, and both may differ from the mechanisms that bring attention back to the task. . This dissertation thus shows that the temporal organization of mind-wandering exists at more than one scale, and that these organizations are themselves informative. At the scale of a single episode, mind-wandering showed clear internal structure, with separable phases of onset, maintenance, and transition out prior to explicit meta-awareness. At the scale of repeated episodes, on-task and mind-wandering periods also showed structure in how they related to each other over time, appearing partly dissociable in some ways and dynamically constraining each other in others.

These are not two separate stories about mind-wandering. Rather, the larger-scale dynamics of moving between on-task focus and mind-wandering appear to emerge from the same kinds of temporal transitions observed within a single episode. In that sense, the single episode is not just one instance of mind-wandering, but the basic unit out of which the broader ebb and flow between on-task and off-task states is built. One implication of this is that future work will need to be more explicit about which temporal scale of mind-wandering it is trying to explain, and at what level of analysis. The present studies suggest that these findings are all part of the same broader temporal organization of mind-wandering, but that this organization does not reveal itself in exactly the same way at every level.

Limitations and Future Directions

A central limitation of the present account is that the mind-wandering onset measure is not perfect. Although the last-remembered-text method provides a much closer estimate of onset than is typically available in this literature, it is still an estimate of when participants were no longer encoding the external material well enough to remember it later. This means it collapses the "drift into" phase of mind-wandering to a single moment. Additionally, because the paradigm depends on self-caught reports, is essentially "blind" to mind-wandering episodes that go unnoticed or resolve without explicit meta-awareness. Additionally, at a theoretical level, the present work says more about the structure and timing of mind-wandering than about its causes. It helps clarify when different phases of an episode occur, but does not yet explain why mind-wandering begins when it does, or what determines when and how it ends. However, these are necessarily temporal questions, and thus while the current work does not address them, it opens the door for future work to examine these questions more directly

Conclusion

The central conclusion of this dissertation is that the temporal dynamics of mind-wandering are not just descriptive detail, but theoretically consequential features of the phenomenon. When episode onset, maintenance, and the period preceding meta-awareness are examined separately, each carries distinct information. The same is true of the broader pattern of moving into and out of mind-wandering across repeated episodes. Treating mind-wandering too coarsely risks collapsing across differences that are central to how it operates. In that sense, temporal dynamics are not peripheral to mind-wandering. They are part of its underlying structure.

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