Extracting blinks from continuous eye-tracking data in a mind wandering paradigm

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ARTICLE INFO

Keywords:

Mind wandering
Eye tracking
Blinking
Data processing

ABSTRACT

Mind wandering is a universal phenomenon in which a person's attention decouples from stimuli within their current environment. Researchers have sought objective, less disruptive indicators of cognitive disengagement, resulting in a focus eye tracking and blink characteristics. Such research has found positive associations between mind wandering and blink characteristics, typically in reading tasks. However, extracting blinks accurately from continuous eye-tracking data is complex, and the literature contains inconsistently reported data processing methods, some of which may have an elevated risk of identifying noise as signal. Further, the relationship between attentional disengagement and blink durations has not been fully explored in multiple task modalities. We conducted three modality-specific experiments while recording eye movements. Blink durations varied as a function of stimulus/task engagingness; less engaging tasks yielded longer blink durations, suggesting a link between blinking and mind wandering. Recommendations are provided for researchers seeking to accurately derive blink events from continuous, binocular, eye-tracking data.

1. Introduction

Eye tracking experiments gather a stream of coordinate data that can be interpreted as fixations and saccades. However, many other metrics are available, such as blinks, which have been explored as a behavioral indicator of psychological states in recent years. Due to the demand for more objective and automated detection systems of phenomena such as mind wandering, drowsiness, and emotional processes, researchers have discovered that characteristics of human blinking may be an informative correlate of fluctuations in cognitive states (Chen & Epps, 2013; Chermahini & Hommel, 2010; Fogarty & Stern, 1989). However, the methods for detecting and extracting blinks in eye-tracking data are not uniform in the literature. Eye-tracking data, like all data sources, contains noise. This is particularly true of eye tracking because samples can be lost for a variety of reasons such as head movements, looks off-screen, and blinks. Therefore, appropriately cleaning and isolating the relevant signal (in this case a blink) is critical to achieving accurate experimental findings using these techniques. While some variability in methods is expected, the parameters of what are labeled as endogenous eye blinks vary between studies to a degree that could affect the significance of results. These parameters are often either underspecified or underreported, and most critically, determined without reference to oculometric data regarding the normal range of human blink characteristics. Consequently, artifacts of noisy data (which would be excluded by more scrupulous parameters) may be falsely identified as blinks, skewing data, and influencing results. The primary objective of this paper is to provide a guide and set of

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tools for researchers seeking to identify blinks within eye-tracking data more accurately. The second objective of this work is to demonstrate its utility as a measurement of not just *if* there is mind wandering, but *how much* the mind is wandering.

1.1. Blinks

The duration of a spontaneous human eye blink is known to be broadly between 100 and 400 ms (Bartoshuk & Schiffman, 1977). The average blink is estimated to take roughly 260 ms with a standard deviation of 11.3 ms (Fatt & Weissman, 2013). Phases of blinks have also been examined. One study reports the average eyelid closing phase to be around 85 ms on average, and the opening phase to be around 200 ms, with the eyelids rarely closing completely (Guitton, Simard, & Codere, 1991). These parameters help define the minimum amount of time in which samples are lost due to physiologically plausible blinks. For example, consecutive sample loss of a duration less than 85 ms is very unlikely, if not impossible, to be a blink.

Most researchers in psychological domains utilize infrared or near-infrared pupil-detecting eye trackers. Consequently, there is an expected difference between eyelid-based measures of blink duration and the time in which the pupils are occluded from the eye tracker, as shown by Hoppe, Helfmann, and Rothkopf (2018). The degree to which these two measures are expected to differ depends on the characteristics of the eyes and blink patterns of each participant (individual differences). The available blink data in eye-tracking paradigms involve a range of time in which both pupils are undetected due to closure of the eyelids. This involves establishing a lower and upper bound on undetected pupil durations which count as blinks, as sample loss can be due to other factors such as eye movements off screen, head movement, poor track accuracy/validity, or intentional eye closure.

Thus, there are currently no conventional standards for blink extraction from continuous eye-tracking data. Table 1 illustrates the variability in the lower boundary criteria for blink extraction parameters in a selection of blink-focused psychological eye-tracking research. This parameter reflects the shortest window of time that continuous pupil track loss is counted as a blink in each study. While blink characteristics may be dependent on participant and task characteristics, there are limits to the speed that spontaneous blinks can reasonably approach. Some data extraction techniques use a blink labeling threshold much faster than what should be possible by even the fastest human blink, while others set the minimum parameter near the physiological average. Setting this threshold too low (e.g., much faster than people can possibly blink) increases the risk of measurement noise being falsely identified as signal (Holmqvist, Nyström, Andersson, Dewhurst, Jarodzka, & Weijer, 2011). Many researchers select a parameter near either 80 or 100 ms, which is more physiologically feasible, but may not always be the optimal choice, depending on several features of design and apparatus. For example, selecting low blink thresholds (especially physiologically implausible ones) is especially risky when using eye trackers with low sampling rates. In these cases, the number of consecutive missing samples being labeled as a blink is so low (typically three, but sometimes as low as one) that the risk of erroneously labeling measurement noise as blink signal is elevated.

1.2. Mind wandering

Research in mind wandering has found a link between eye blink characteristics and mind wandering episodes, making it a strong candidate for investigating optimal blink extraction methods. Mind wandering is a state of moving from one thought to another internally, uncoupled from external stimuli (Smallwood & Schooler, 2006). Without focus on external stimuli we cannot process or learn new material, nor can we perform goal-oriented interactive tasks which require attention, perceptual or cognitive processing, and actions. While there are circumstances in which mind wandering is adaptive and beneficial (Chermahini & Hommel, 2010; Mooneyham & Schooler, 2013), a meta-analysis suggests that it is detrimental to performance in cognitive tasks ranging from signal detection to text comprehension (Randall, Oswald, & Beier, 2014). A range of studies also indicate that mind wandering occurs at least 20% and up to 50% of the time, even during tasks that are not designed to induce it (Faber, Bixler, & D'Mello, 2018; Kane et al., 2007; Killingsworth & Gilbert, 2010; Schooler, Reichle, & Halpern, 2004; Smilek, Carriere, & Cheyne, 2010). In laboratories, classrooms, and beyond, the need to detect mind wandering in order to account for and ameliorate its effects is evident. Much progress has been made in the area of interventions and detection of mind wandering in recent years, including putting people into a growth mindset (Mrazek et al., 2018).

Table 1
Examples of blink extraction parameters.

Reference	Minimum blink criterion (ms)	Sampling rate (Hz)
(Ahlstrom & Friedman-Berg, 2006)	200	60
(Brouwer, Van Ee, & Schwarzbach, 2005)	20	50
(Faber et al., 2018)	83	120 & 60
(Frank et al., 2015)	100	120
(Geng, Ruff, & Driver, 2009)	50	60
(Huette, Mathis, & Graesser, 2016)	100	60
(Smilek et al., 2010)	3	1000
(Van Orden, Limbert, Makeig, & Jung, 2001)	83.3	60
(Walcher, Körner, & Benedek, 2017)	6	500
(Bixler, Blanchard, & Garrison, 2015)	Not directly reported	300 & 60
(Krasich et al., 2018)	Not directly reported	1000
(Zhang et al., 2021)	50	5000

Note. "Minimum blink criterion" refers to the amount of time that samples must be consecutively missing in order to label an event as a blink.

Most of the research in this domain has relied on the subjective metacognitive judgments of participants in order to measure mind wandering. This includes self-caught and retrospective methods, in which participants freely report instances of mind wandering either during or after a task, and probe-caught methods, in which tasks are periodically halted in order to ask participants whether their attention was elsewhere. While these methods have yielded valuable results, three disadvantages can be identified in their usage. First, they are subjective, which invites inaccuracies in self-reporting for both intentional (e.g. social desirability bias) and unintentional (e.g. unawareness of mind wandering) reasons. Probe-caught and self-caught methods rely on participants having meta-awareness of their own cognitive states at any given time, but it's well established that people are sometimes unaware of their own thought processes (Schooler et al., 2011). Second, self-report methods are disruptive of participants' natural fluctuations of attention during a task; task-concurrent self-reports may artificially inflate attentional engagement (Seli, Carriere, Levene, & Smilek, 2013). Third, these methods often dichotomize mind wandering into binary states of on- and off-task, which may neglect some important nuances in the phenomenon (Weinstein, 2018). A small but important section of the literature demonstrates that attention-task decoupling can, in fact, be gradual (Schad, Nuthmann, & Engbert, 2012; Singh & Fawcett, 2008). Therefore, measurements that can capture gradations in attentional decoupling should provide a more nuanced and account of mind wandering.

More recently, researchers have addressed these issues by exploring the biometrics of mind wandering, finding success with eye blinks (Frank, Nara, Zavagnin, Touron, & Kane, 2015; Grandchamp, Braboszcz, & Delorme, 2014; Uzzaman & Joordens, 2011). The summative conclusion across multiple studies is the rate and duration of blinks are positively correlated with episodes of mind wandering. Subsequently, researchers have developed automated detection systems of mind wandering in which blink rate plays a crucial role alongside other eye-based measurements (Bixler & D'Mello, 2014, 2016; Blanchard, Bixler, & Joyce, 2014; Faber et al., 2018). These systems have been employed in task modalities including reading (Bixler & D'Mello, 2016; D'Mello, Kopp, Bixler, & Bosch, 2016; Mills & D'Mello, 2015), scene viewing (Krasich et al., 2018; Zhang, Anderson, & Miller, 2021), film viewing (Mills, Bixler, Wang, & D'Mello, 2016), and more (Faber, Krasich, Bixler, Brockmole, & D'Mello, 2020). By utilizing these systems, which are primarily based on supervised machine learning, more general learning and classroom-approximate tasks have become incorporated as well (2017; D'Mello, Dieterle, & Duckworth, 2017; Hutt, Mills, White, Donnelly, & D'Mello, 2016). However, most of the eye-tracking studies of mind wandering that include blink information primarily focus on rate and ignore duration. While blink rate has been linked as evidence of mind wandering in many tasks, blink duration has not been verified so widely. As a result, there are many other task modalities to be explored using blink duration, each of which may influence how cognitive disengagement and eye movements interrelate. In the present research we explore the relationship between mind wandering and blinking across multiple sensory modalities.

Blinking and other eye movement behaviors are useful as measurements of mind wandering. Understanding why this may be the case, however, requires inspection of additional literature. The mechanism behind blinking's relationship with mind wandering may lie within the default mode network, a pattern of connections in the brain associated with inattention, daydreaming, and mind wandering (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Mason et al., 2007; Raichle, 2015). The default mode network is also active during many phenomena that are not associated with present external stimuli, such as thinking about the self, interpreting past events, or planning (Qin & Northoff, 2011; Spreng & Grady, 2010). One series of studies have shown that while watching a film, participants' blinks were linked with subsequent momentary activation of neural areas consistent with the default mode network (Nakano, 2015; Nakano, Kato, Utsuke, Itoi, & Shigeru, 2013). Importantly, the default mode network was not activated when the film was temporarily and sporadically blacked out at a rate that resembles average blink patterns. Thus, the act of blinking itself, not just momentary decoupling from the stimulus, may be actively involved in the process of attentional disengagement via activation of the default mode network. It follows that blinking more often and for longer periods of time would generate more activity in the default mode network, thereby increasing the frequency and depth of mind wandering episodes. This is consistent with the findings of the data mining and cognitive experimental approaches to the literature discussed earlier, supporting the validity of blink characteristics as an operationalization of mind wandering.

While blinks have been associated with mind wandering in previous research, less is known about the gradience and temporal dynamics of behavior when transitioning from a state of tight attentional coupling with the external stimulus to detachment. Being able to detect when someone is about to begin mind wandering has been steadily progressing in recent years, showing that we are advancing from describing the phenomenon to being able to predict when it happens (Bixler & D'Mello, 2014; Blanchard et al., 2014). Further, it may be of use to develop systems that detect not only whether the mind is wandering, but the degree to which the mind is disengaged. Recent neuroimaging work supports the notion of gradual decoupling as well (e.g. Murphy et al., 2018, 2019), but neuroimaging is expensive, time-intensive, and less readily available to researchers seeking to measure attention and mind wandering. Eye tracking may be a good middle-ground for not only identification of mind wandering, but the degree of decoupling from external stimuli as well. Along these lines, blink durations, as a temporal measure, may be useful as a tool to observe gradience in mind wandering in ways that blink rate may not.

Most eye trackers cannot directly report whether samples are lost because of blinks, inaccuracy in calibration, head turns, or off-screen fixations. It is important to define blinks as binocular data events within a specified range of possible durations. Single eye track loss is likely due to track loss from calibration error, extremely short binocular track loss is likely due to measurement noise, and extremely long binocular track loss is likely due to looks far off screen or intentional eye closures. In the present study, we show that an overinclusive range of what are considered blinks can in a change in significance during hypothesis testing. The thresholds used to define blinks are vital to achieving accurate and valid results. This study included tasks across three different modalities, and a description of methods on how eye blinks were extracted from a Tobii X2 system's data. Tobii's data recording and output is similar to that of other systems, such as EyeLink, so the methods and resources provided here can be used with any binocular eye tracking system.

2. Experiment 1

Before eye-tracking data can be used to assume mind wandering in participants, the stimuli and tasks involved must be shown to elicit different levels of mind wandering using conventional measures. Mind wandering happens in many kinds of situations, so any tool used to detect it must be robust to task differences (Faber et al., 2020). To validate a range of stimuli for use in an eye-tracking study, we examined different tasks in three modalities, including reading, visual search and counting, and listening to speech while viewing a blank screen. Each task type contains stimuli which were hypothesized to vary by degrees of engagingness and induce different levels of mind wandering. To ground this validation in the literature, we used a self-caught mind wandering paradigm and a retrospective task engagingness survey, both consistent with similar measures used in previous studies of mind wandering (Weinstein, 2018).

2.1. Method

2.1.1. Participants

This study was approved by the University of Memphis Institutional Review Board. Forty-one students participated in exchange for course credit in an undergraduate psychology course. Participants were all right-handed native English speakers with corrected-to-normal or normal vision by self-reported criteria. The study was not advertised as a mind wandering study to prevent self-selection. Participants completed this experiment online in a single session, using their own computers.

2.1.2. Materials and measures

For the reading condition, three different text passages were selected of the same genre, all historical in nature. These passages were selected for to test their variability in mind wandering elicitation. Specifically, the topics were an article on the Salem witch trials (Flesch-Kincaid Grade Level = 10.3) a reading on law and punishment in Plymouth colony (Flesch-Kincaid = 13.6), and a section of the Constitution of the United States (Flesch-Kincaid = 23.1). Readings were presented one page at a time with 25 lines of text on screen, sans-serif font size 31, single-spaced, and were four pages long. This format was chosen to increase ecological validity of having as much text on the screen as possible, as well as minimize participants' actions advancing the text, thereby decreasing potential interruptions to any mind wandering that occurred. No time limit was imposed during the reading condition. Overall, this condition took participants roughly 12 min on average (witch trials $M_{\text{time}} = 3.84$ min, $SD = 2.31$ min; Plymouth law $M_{\text{time}} = 4.22$ min, $SD = 2.76$ min; Constitution $M_{\text{time}} = 4.30$ min, $SD = 2.08$ min).

For the visual condition, participants completed two tasks with accompanying static images. In a counting task, participants were presented with an image of a few hundred penguins huddled together and instructed to count the penguins within 100 s. In a target-

Fig. 1. Examples of visual stimuli used in reading (a), counting (b), search (c), and audio (d) tasks.

absent visual search task, participants were presented a Where's Waldo visual scene in which Waldo was digitally edited out and were instructed to try to find Waldo within 100 s. Fig. 2 displays the stimuli present in each condition. Both images were presented full-screen.

For the audio condition, participants listened two five-minute audio clips. One of the clips used the audio of a TED talk on the topic of sound design (Flesch-Kincaid = 6.4), in which the speaker had prosodic variability, and several sound effects were used as demonstrations including birdsong, construction work, and traffic. The other clip used a selection from a high-level pharmacology lecture (Flesch-Kincaid = 10.7), which involved the heavy use of jargon, no sound effects or music, and more monotonous speaker. The computer screen was completely black for the duration of the audio clips. Participants were instructed to listen to the audio while looking at the screen and minimizing head movement (to resemble the instructions of an eye-tracking study). An example of the stimuli used in each modality condition is displayed in Fig. 1.

The dependent variables in this experiment were the frequency of self-caught instances of mind wandering and self-reported task engagingness. The measurement of these variables were informed by a *meta-analysis* of probe-based mind wandering research (Weinstein, 2018). During each task, participants were instructed to click their mouse each time they caught themselves mind wandering, defined as when their attention was not on the task at hand. Task engagingness was measured via a 6-point Likert-type survey item at the end of each task which read "How engaging did you find that task?" The response options ranged from "very boring" to "very engaging." This survey, including all instructions and materials, can be viewed in its entirety on the project's OSF page, found at osf.io/b2rg4.

2.1.3. Procedure

Each participant performed every task within each modality condition. Tasks were counterbalanced within modality conditions, but the modality conditions themselves remained in a fixed order (reading, then visual, then audio). The click-based self-caught mind wandering instructions were given before each task, and a self-reported task engagingness survey item was given immediately following each task.

2.2. Results

To examine how much mind wandering was elicited by each task, we analyzed the frequency of mouse clicks within each modality condition. This self-caught mind wandering measure was frequency data which was skewed and zero-inflated, and the standard deviations were larger than the mean in each condition. Accordingly, we conducted a Negative Binomial (NB) and a Zero-Inflated Negative Binomial (ZINB) Regression analysis to account for these characteristics while predicting click counts based on task within each modality condition. These models were analyzed using the *pscl* R package (Zeileis, Kleiber, & Jackman, 2007) and compared using the Vuong test (Vuong, 1989) to determine if the ZINB model was superior to the NB model in each case. To determine the relative levels of engagingness of each task, we conducted paired samples t-tests on the self-report scale data by task within each modality condition, except for the reading condition, for which we used a repeated-measures ANOVA because it involved three tasks. A descriptive summary of these measures is depicted in Table 2. A summary of the results of the self-caught mind wandering regression analyses is depicted in Table 3.

Participants were instructed not to do anything else on their computers during the experiment, but not all participants complied. As a result, attrition was a minor factor. The number of participants who fully completed each task in each modality is also included in Table 2. Data from participants who did not fully complete all tasks within a modality were excluded from that modality's analyses.

For the reading condition, the repeated measures ANOVA conducted on the task engagingness survey data revealed that the

Fig. 2. Histograms of binocular pupil detection loss in each task modality. Note. Each bin corresponds to the length of time of one sample at 60 Hz. For the purposes of this visualization, the minimum duration represented is 83 ms. The dashed line represents the imposed 160 ms threshold.

Table 2

Descriptive statistics of self-caught mind wandering and engagingness of materials. All cells contain M (sd).

Data type	Reading (N = 31)			Visual (N = 34)		Audio (N = 27)	
	Constitution	Plymouth Law	Witch trials	Search	Counting	Pharmacology	Sound design
Self-caught MW ^a	6.03(7.41)	4.58(6.95)	3.13(3.96)	2.68(5.19)	2.85(2.74)	7.81(10.3)	4.33(5.94)
Engagingness ratings ^b	2.16(1.46)	3.65(1.60)	4.42(1.52)	4.00(1.89)	2.53(1.76)	3.44(1.64)	3.81(1.64)

^a Self-caught mind wandering data were obtained by instructing participants to click their mouse every time they realized they were mind wandering. Greater numbers indicate more mind wandering, and thus lower levels of engagement.

^b Task engagingness rating data were obtained from a 6-point Likert-type scale ranging from “very boring” (coded 1) to “very engaging” (coded 6). Greater numbers indicate greater levels of engagement.

Table 3

Regression analyses of self-caught mind wandering data.

Parameter	Reading				Visual				Audio			
	NB		ZINB		NB		ZINB		NB		ZINB	
	β	z	β	z	β	z	β	z	β	z	β	z
Intercept	2.14	6.18*	2.06	7.78***	0.92	0.51	1.30	2.22*	2.65	3.82***	3.06	7.09***
Coefficient	-0.33	-2.01*	-0.26	-1.47	0.06	0.32	-0.13	-0.36	-0.59	-1.34	-0.56	-2.00*
Vuong test				0.444				0.527				3.204***

Note. Reading tasks were coded as Constitution = 1, Plymouth law = 2, witch trials = 3.

Visual tasks were coded as Waldo = 1, Penguins = 2.

Audio tasks were coded as Sound design = 1, Pharmacology = 2.

* $p < .05$, *** $p < .001$.

different passages elicited different levels of engagement, $F(2, 60) = 27.101$, $p < .001$. Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated $\chi^2(2) = 2.646$, $p = .266$. Post hoc comparisons with Fisher's Least Significant Difference indicated that the witch trials passage was significantly more engaging than the Plymouth law passage, $t(30) = 6.234$, $p < .05$, and the Constitution excerpt, $t(30) = 41.619$, $p < .001$, while the Plymouth law passage was more engaging than the Constitution excerpt $t(30) = 145.946$, $p < .001$. Regarding self-caught mind wandering regression analyses, the Vuong test revealed that the ZINB model was not superior to the NB model. Within the NB model, passage condition was significantly associated with a change in self-caught mind wandering instances, $\beta = -2.103$, $p < .05$, such that passages rated as less engaging elicited more mouse clicks. This supports the hypothesis that that each of the passages elicit different amounts of mind wandering and varied in subjective engagingness.

For the visual tasks, a paired samples t -test of the self-report data indicated that the search task (Waldo) was reported to be significantly more engaging than the counting task (penguins), $t(33) = 3.729$, $p < .001$. The Vuong test of the regression models revealed that the ZINB model was not superior to the NB model, which yielded no significant predictors. The hypothesis that the tasks elicit different amounts of mind wandering is only supported indirectly by the engagingness survey data.

For the audio tasks, a paired samples t -test of the task engagingness survey data did not reveal a significant difference between the two conditions $t(26) = 1.264$, $p = .218$. However, the Vuong test of the regression analyses indicated that the ZINB model was superior to the NB model, and that the sound design condition was associated with fewer instances of self-caught mind wandering, $\beta = -0.561$, $p < .05$. The hypothesis that the audio clips elicit different amounts of mind wandering is supported by the self-caught data.

2.3. Discussion

The purpose of this experiment was to validate our stimuli and tasks for use in an eye-tracking study of mind wandering. One of the primary goals of using eye-tracking data to detect mind wandering is that it is not intrusive, disruptive, and does not bring attentional processes into the awareness of the participants. For this reason, this initial experiment was conducted in order to establish variability in the elicitation of mind wandering observed by self-caught and probe-based measures so that we can make inferences about whether mind wandering may be happening in participants who are not probed. We observed differences in the amount self-caught mind wandering between tasks across multiple modalities. We can attempt to generalize these findings to other, non-probed participants. More specifically, if a task elicited more mind wandering on average in this experiment, then we have justification in assuming that it will also elicit more mind wandering on average in a similar sample of participants whose blink behaviors will be examined. In this way, we can begin to establish the link between mind wandering and blink durations.

Generally, our hypotheses were supported and our materials were validated, but there were some flaws. The reading passages elicited the expected pattern of results. Mind wandering episodes linearly increased as a function of passage. More specifically, the Constitution excerpt elicited more mind wandering than the Plymouth law passage, which elicited more mind wandering than the Salem witch trials passage. The inverse trend was true of engagingness ratings, further supporting the use of these materials. The visual tasks elicited differences in engagingness ratings, but not mind wandering episodes. One possible explanation of this nonsignificant effects is that these tasks are short in comparison to the other modalities, and participants may not have had time to catch themselves

mind wandering. Another possible explanation is that the tasks involved may have been too cognitively involved for much mind wandering to have occurred, especially within a limited timeframe. The audio condition, however, did reveal significant differences in self-caught mind wandering such that more mind wandering was observed in the pharmacology lecture than the sound design presentation. While the engagingness survey results were not significantly different between these two stimuli, we can at least observe the mind wandering results some support for our hypotheses and justify its use in the following eye-tracking study.

3. Experiment 2

By using the same tasks and stimuli with a new set of participants, we seek to generalize the mind wandering elicitation properties of each task while observing blink durations. We predicted that blink durations would increase during tasks that elicited more mind wandering in each modality. While blink rate has been associated with mind wandering across many tasks, establishing a similar association with blink duration may provide additional insight into the cognitive mechanisms of mind wandering as they relate to eye movement behavior. In the following study, across multiple tasks, we hypothesized that successive levels of mind wandering properties would be associated with a linear increase in eye blink duration if mind wandering is a gradual decoupling process. If mind wandering is instead a discrete on/off process, the averages may still increase linearly, but the data would also exhibit a bimodal distribution: one mode of a shorter duration when attending, and a mode at a longer duration for times of mind wandering. Bimodality was tested in each experiment to rule out this possibility.

There were no probes and no self-monitoring instructions during eye-tracking data collection to ensure that participants were not interrupted and were not made aware of their attentional processes or the purpose of the study. This was done to verify that this method eliminates the need for intrusive task modifications that would and to establish blinks as a covert means of detecting or monitoring mind wandering.

3.1. Method

3.1.1. Participants

This study was approved by the University of Memphis Institutional Review Board. Thirty undergraduate students participated in exchange for course credit in an undergraduate psychology course. Each participant took part in all three tasks, which were conducted consecutively. Participants were all right-handed native English speakers with corrected-to-normal or normal vision by self-reported criteria. The study was not advertised as a mind wandering study to prevent self-selection. Participants completed this experiment in a single laboratory session.

3.1.2. Materials, measures, and eye-tracking apparatus

The materials, tasks, and instructions were nearly identical to those used in Experiment 1, but all mentions of mind wandering and task engagingness were omitted. The three passages in the reading condition, both tasks in the visual condition, and both audio clips in the audio condition were presented in the same way, but participants were not informed of mind wandering, were not asked to make any mouse clicks, and did not complete any survey questions about engagingness. Rather, participants completed these tasks while seated at a computer with an eye-tracking apparatus.

This experiment was built using Tobii Studio, and a Tobii X2-60 eye tracker was used to track eye movements at a sampling rate of 60 Hz. The eye tracker was calibrated using a nine-point procedure at the beginning of the study. Participants were instructed to remain still, but no head mount was used. The primary dependent variable in this experiment was the duration of participants' eye blinks, defined below in Section 2.1.3.

3.1.3. Blink extraction and data processing

To determine a blink with high confidence, we used only timepoints where both eye tracks were lost. Both eyes were used and matched at each timepoint to see if one or both samples were present or missing. Each timepoint was marked as either track valid and present for both eyes, one eye valid and present only, or neither eye valid nor present. If both eye samples were missing, these time points were counted as ones, and present samples were counted as zeros. The position of the eye was not considered in the current analysis. What remained was a vector indicating track loss for both eyes over the course of each task, which was linked with vectors of participant information and the task being performed. Only samples where the participant was performing a task were used (i.e. instructions and calibration/drift correction screens were not used). Consecutive missing samples were then counted and multiplied by 17, the approximate number of milliseconds between each sample taken by an eye tracker at 60 Hz, thereby computing sample loss durations. The data was filtered so that only samples with both eyes missing were included. Sample loss durations of over 1000 ms were considered to be beyond the range of spontaneous blinks and were therefore excluded. MATLAB code and deidentified data used in this analysis are available online at osf.io/b2rg4.

As described in Section 1.1, there is no consensus on the best way to determine the most appropriate lower blink threshold parameter. To inform our parameter selection, we examined the distribution of our observed data along with oculometric data of typical human blink durations (Fatt & Weissman, 2013; Guitton et al., 1991). Fig. 2 displays the distributions of binocular sample loss durations less than 1000 ms across each task modality. We calculated Hartigan's dip statistic to determine whether this distribution was unimodal (Freeman & Dale, 2013; Hartigan & Hartigan, 1985; Mechler, 2002). This test revealed that the distribution was bimodal during the reading condition ($HDS = 0.04, p < .001$), visual condition ($HDS = 0.03, p < .001$), and audio condition ($HSD = 0.04, p < .001$).

Importantly, these cases of bimodality appear to be due to measurement noise, not due to two distributions of blinks. More specifically, the lower mode is likely due to measurement noise, and the higher mode is likely the actual distributions of reliably identified blinks. In support of these claims, we note that the lower distribution consists of sample loss durations less than 160 ms, which is 9 standard deviations below the mean blink duration of 260 ms reported by Fatt and Weissman (2013). This suggests that most of the durations found in this lower distribution are faster than what should be possible by a human eye blink based on physiological oculometric data. Consecutive sample loss for less than 160 ms was therefore excluded from analyses in all three conditions. This excludes roughly 42% of missing sample data, which may be due to momentary track quality issues, head movements, saccadic sample loss, all of which are within timeframes that are significantly faster than a human blink. While this proportion may seem high, the nature of the excluded data would lead us to expect this kind of proportion. Instances of sample loss at short durations have many more opportunities to occur than instances of sustained sample loss, especially in this analysis of raw eye-tracking data. Most studies tend to report pre-processed data using software that automatically excludes noisy samples. In a typical eye tracking experiment, 100% of these datapoints are discarded as noise if the researcher is looking at fixations or saccades, whereas we were able to find signal in 58% of it. Further, other studies that observe blinks (see Table 1) do not report how much data is excluded by their various blink parameters, obscuring the frame of reference for this proportion. We chose this cutoff at the lowest value that would include as much signal data as possible.

3.1.4. Procedure

Participants were seated in a stationary chair in front of a computer equipped with the eye eye tracker. The research assistant briefly outlined the experiment and informed participants to use the space bar to advance through each page of the experiment. Participants were further instructed to hold their heads steady during the experiment and to not stare off screen. The eye tracker was then calibrated, and the experiment was started. Verbal instructions were given, immediately followed by verbatim written instructions. Participants were not able to backtrack through the readings once they had advanced to the next page.

The instructions to each task were identical to those in Experiment 1, but mind wandering and task engagingness were not mentioned. Also aligned with Experiment 1, the tasks within each modality were counterbalanced across participants, but the order of the modalities themselves remained fixed (reading, then visual, then audio).

3.2. Results

In order to examine the relationship between mind wandering and blink durations, we used R (R Core Team, 2020) and lme4 (Bates, Mächler, Bolker, & Walker, 2014) to perform linear mixed effects analyses for each task modality.

In the reading condition, text condition was entered as a fixed effect, while subjects were entered as a random effect, and by-subject random slopes were also included in the model. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. One participant was excluded in this condition for poor track quality (>10% of total samples missing). A p-value was obtained by a likelihood ratio test of the full model against a model without the task condition. This analysis revealed that increasing text condition affected blink durations ($\chi^2(2) = 38.92, p < .001$), increasing them by about 10.7 ms $\pm$ 9.2 (standard errors) from the most engaging (witch trials) condition ($M = 384.2, SD = 168.3$) to the medium condition (Plymouth law) ($M = 369.9, SD = 148.5$), and 8.9 ms $\pm$ 9.7 to the least engaging (Constitution) condition ($M = 365.1, SD = 143.8$) when controlling for participant effects. This fit our predicted pattern of longer blink durations for less engaging readings, which also elicited more self-caught mind wandering episodes in Experiment 1.

In the visual condition, task condition was entered as a fixed effect, and subjects were again entered as a random effect with by-subject random slopes. Nine subjects were excluded from this analysis for poor track quality. This analysis did not reveal a significant effect of task condition on blink durations ($\chi^2(1) = 2.32, p < .13$), which increased by about 24.0 ms $\pm$ 14.9 (standard errors) from the search task (Where's Waldo: $M = 358.1, SD = 166.2$) to the counting task (Penguins: $M = 387.1, SD = 165.2$) when controlling for participant effects.

In the audio condition, task condition was again entered as a fixed effect, and subjects were again entered as a random effect with by-subject random slopes. Six participants were excluded from this analysis for poor track quality. This analysis revealed that auditory stimulus affected blink durations ($\chi^2(1) = 5.19, p < .05$), increasing them by about 14.7 ms $\pm$ 6.2 (standard errors) from the sound design condition ($M = 376.0, SD = 148.0$) to the pharmacology condition ($M = 385.3, SD = 151.6$) when controlling for participant effects. This fit our predicted pattern of longer blink durations for the less engaging audio clip, which also elicited more self-caught mind wandering episodes in Experiment 1.

To illustrate the importance of determining and justifying appropriate blink extraction parameters, we wanted to explore the possibility that inclusion of the lower tail of the distribution would still yield significant results. To examine the effect of our minimum duration criterion of blinks, we conducted identical linear mixed-effects analyses, except all blink durations less than 1000 ms were included. This is a proxy of the data processing methods of other studies that contained a lower threshold (see Section 1.1). As predicted, under this condition, the likelihood ratio test of the models were nonsignificant in the reading condition ($\chi^2(2) = 2.14, p = .34$), visual condition ($\chi^2(1) = 1.12, p = .29$), and audio condition ($\chi^2(1) = 0.04, p = .95$). Given that the results above generally indicate that longer blink durations are associated with tasks that elicited more self-caught mind wandering in Experiment 1, as well as physiological data that show that blink durations are unlikely to occur in this range (Fatt & Weissman, 2013; Guitton et al., 1991) these comparisons support the hypothesis that durations less than 160 ms are due to noise rather than extremely short blinks, providing justification for our selected lower threshold.

3.3. Discussion

We predicted that tasks which elicit more mind wandering would yield longer blink durations. Experiment 1 demonstrated that some tasks elicited more mind wandering than others, and that some tasks were more engaging than others. Generally, we found that the tasks which elicited more self-caught mind wandering in Experiment 1 also elicited longer blink durations in this experiment. While these participants never directly rated the mind wandering elicitation properties of our materials, the pattern of results with blink durations matched the pattern of results we found with participants who did directly rate and report mind wandering in Experiment 1.

In the reading condition, we found that passages that elicited more mind wandering and were rated as less engaging yielded longer blink durations, supporting the hypothesized relationship between blink durations and mind wandering during reading. Specifically, there was a linear trend in self-caught mind wandering, engagingness ratings, and blink durations across the three selected texts. These results show a pattern supporting the hypothesis that there are degrees of decoupling from external stimuli as a function of task engagingness, and that blink durations being a sensitive and informative measurement of gradient mind wandering.

In the audio condition, the self-caught mind wandering data in Experiment 1 indicated that the pharmacology lecture elicited more mind wandering than the pharmacology lecture, which was expected given the nature of the stimuli. This effect was not reflected in the engagingness ratings, which may be due to a variety of factors, such as task length or the lack of visual stimuli. However, the pharmacology lecture yielded longer blink durations than the sound design presentation. This result further supports the hypothesized relationship between blink durations as an observation of mind wandering. Importantly, this demonstrates that blink durations are a useful tool for studying mind wandering outside of visual paradigms. A visual stimulus is not necessary for longer blink durations to be associated stimuli that elicit increased mind wandering. Therefore, mechanisms through which blinking is linked to mind wandering are not necessarily due to the temporary loss of visual information during each blink. This is consistent with the findings of Nakano et al. (2013), who arrived at this conclusion by simulating visual loss during blinks by intermittently blacking out the computer screen during film viewing, and found an association between spontaneous blinks, but not blackouts, and default mode network activation. Our findings in this experiment support this conclusion because there were no relevant visual stimuli to lose sight of during blinks, but the expected relationship between blink durations and stimulus mind wandering still occurred.

In the visual condition, the search task was rated as significantly more engaging than the counting task within engagingness survey data in Experiment 1, but this effect was not reflected by the self-caught mind wandering data. The analysis of blink duration data was nonsignificant. While the pattern of the blink duration data was consistent with the direction of our prediction, we would not interpret this as support for our hypotheses. Further, the fact that neither task yielded more self-caught mind wandering episodes in the Experiment 1 may indicate limitations in this design. There are several explanations for the lack of findings here that must be addressed. First, this task modality was relatively short in comparison to the other modality. It could be the case that participants were given enough time for their minds to wander. Second, the two tasks in this modality involve more disparate cognitive processes than tasks within other modalities. Counting and searching may not be as directly comparable as reading boring or engaging texts. Further, the cognitive operations involved in these tasks may have given participants enough to focus on such that mind wandering rarely occurred. Addressing these limitations, future research should examine more directly comparable iterations of boring and engaging visual search and counting tasks and increase their duration. Some research has already examined automated mind wandering detection in some visual tasks, such as scene viewing, (Krasich et al., 2018; Zhang et al., 2021), but exploring visual tasks which require additional cognitive operations may be a use avenue of research. Additionally, visual search and counting tasks may elicit different patterns of eye movements, altering the effectiveness of comparing oculometric data for cognitive purposes between them. Future research may account for differences in other eye movement patterns between different task types.

4. General discussion

This series of experiments explored the theoretical link between the duration of blinks and mind wandering, as well as data processing methods for analyzing blinks. Previous literature suggests that mind wandering and blinking are mechanistically related, potentially via transitory activation of the default mode network. We postulated that tasks which induce more mind wandering would also increase average blink duration during their performance. Our findings support this hypothesis in different task modalities, especially reading and auditory modalities. The results of Experiment 1 are important to validate our task and stimulus selections as functional manipulations likelihood of each condition to induce mind wandering. The dual components self-caught mind wandering measurements and task engagingness survey items, which are reflective of common subjective mind wandering research methods (Weinstein, 2018), generally establish this validation. The results of these measures supported the structure of our manipulations and analyses, though some variability was found in these data, which further underscores the importance of more objective measurements of mind wandering. In general, we found that blink durations vary as a function of the likelihood of each stimulus to elicit mind wandering in similar participant samples, indicating that blink durations may be useful to observe gradient mind wandering.

The current study compliments the literature by providing evidence of a measure that may help achieve probeless, nondisruptive, judgment-independent observations of mind wandering. In this context, we conclude that the apparent relationship between blink durations and mind wandering may help inform an objective and gradient approach to measuring mind wandering, which may work in concert with other eye-tracking measurements. These findings are importantly distinct from similar studies in two ways. First, most automated mind wandering detection studies place an emphasis on blink rate rather than duration, but we have shown that duration may be important to consider as well. Second, we have demonstrated these effects across multiple types of tasks, including tasks which do not involve visual stimuli. The finding that blink characteristics may be associated with mind wandering regardless of the modality

of stimuli may be informative to the cognitive mechanisms which drive this relationship.

The other objective of this study was to provide a guide for extracting blinks accurately from eye-tracking data. Holmqvist et al. (2011) illustrate that the measurement noise of a few consecutively missing samples can affect attempts at identifying blinks within continuous eye-tracking data. While the need for blink extraction parameters in any relevant study is clear, the methods of determination of these criteria are often underspecified, underreported, or weakly justified in existing literature. Some reported criteria are insensitive to the physiological characteristics of spontaneous blinks to a degree that elevates the risk of noise being identified as signal. Examination of the distribution of sample loss durations is useful in determining this parameter. Inspection of our data reveals an otherwise normal distribution of blink durations that overlaps toward its lower tail with a distribution of measurement noise. We can assume this lower distribution is in fact mostly noise because physiological data suggest that it is highly unlikely for a spontaneous human blink to occur within this range (Fatt & Weissman, 2013; Guitton et al., 1991; Holmqvist et al., 2011).

We chose to minimize the risk of false blink identification by identifying the point at which these two distributions overlapped and excluding data below this point from analyses. This overlapping point was consistent across all three experiments, and the remaining data was well within the range of acceptability for the assumptions of our analyses. Further, we tested whether having selected a much lower parameter would have affected the significance of our results. Several studies utilize a minimum blink duration criterion smaller than the rate of a single sample of a 60 Hz eye tracker, so we simulated these parameters by doing away with a minimum boundary, as some studies define blinks as any missing sample. When we included every instance of binocular sample loss as a blink, each significant result we previously found became nonsignificant. Parameters that include this type of noise would erroneously increase extracted blink rates, decrease average blink durations, and increase labeled blink rate. While doing so would have resulted in nonsignificance in our analyses, it could also be the case that other analyses that rely on these extracted measures may be swayed from true nonsignificance into false significance due to these factors, especially for studies focusing on blink rate. Directionality notwithstanding, we have demonstrated that choosing an inappropriate blink extraction parameter can influence the results of hypothesis testing.

We have also demonstrated one viable way of determining an appropriate criterion for blink extraction methods. The data remaining after exclusion was within the ranges of normal human blinks and was normally distributed. Future research regarding blinks should involve consultation with observed durations of pupil sample loss to determine boundary selection. It could be the case that our apparatus, software, or design creates bias in our observed durations. As such, we do not endorse 160 ms as the sole standard for blink extraction minimums. Rather, we encourage researchers to consider physiological data and examine the distributions observed in their own data to determine the optimal point at which noise is minimized and accurate blink counts are maximized.

Ours is only one technique which may be used in conjunction with others for additional accuracy. For example, some researchers have employed techniques in which two sets of sample loss that are separated by a small amount of time are combined under the assumption that they are the product of the same blink event separated by a small amount of false positive samples (Grandchamp et al., 2014; Siegle, Ichikawa, & Steinhauer, 2008). It could also be possible that blinks are accompanied by quick downward saccades. If gaze position data is available, these artifacts could be used to distinguish between sample loss due to eye closures and loss due to other error. For example, Ahlstrom and Friedman-Berg (2006) included both a minimum sample loss duration threshold and minimum gaze coordinate velocity threshold within consecutive samples to define blinks. However, our method demonstrates that justifiable blink extraction parameters can be established in the absence of gaze data. As a field, we have yet to determine a singular, optimal method for blink extraction. However, consideration of results and techniques such as these may help researchers develop more optimal data processing techniques with eye-tracking data.

Mind wandering is a universal phenomenon with several psychological, behavioral, and physiological indicators, one of which is blink duration. In many cases, less engaging stimuli and tasks induce more mind wandering. By selecting task and stimuli which elicit difference levels of mind wandering, we observed changes in blink durations. Further, we found a bimodal distribution of sample loss in the eye-tracking data, indicating two different phenomena were observed: blinks and sample loss due to other factors (noise). Significant results were found only by setting a justifiable minimum duration threshold for considering data points to be blinks. Future studies involving eye blink measurements should report and justify blink extraction parameters. With further support from future research, blink durations may provide a window into the mechanisms of when and how a mind gradually decouples from the environment and moves toward an inward trajectory of thought.

CRediT authorship contribution statement

John Hollander: Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Visualization. **Stephanie Huette:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Visualization, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by NSF grant #1108845 to Sidney D'Mello and Art Graesser. Thank you to Sidney D'Mello, Art Graesser, and Andrew Olney for their helpful comments on this work.

Open practices statement

MATLAB code, data, and materials used in this paper are available at osf.io/b2rg4. Experiments were not preregistered.

References

- Ahlstrom, U., & Friedman-Berg, F. J. (2006). Using eye movement activity as a correlate of cognitive workload. *International Journal of Industrial Ergonomics*, 36(7), 623–636. <https://doi.org/10.1016/j.ergon.2006.04.002>
- Bartoshuk, L. M., & Schiffman, H. R. (1977). Sensation and Perception: An Integrated Approach. *The American Journal of Psychology*, 90(4), 718. <https://doi.org/10.2307/1421748>
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *arXiv preprint arXiv:1406.5823*.
- Bixler, R., Blanchard, N., Garrison, L., & D'mello, S. (2015). Automatic detection of mind wandering during reading using gaze and physiology. *ICMI 2015 - Proceedings of the 2015 ACM International Conference on Multimodal Interaction*, 299–306. <https://doi.org/10.1145/2818346.2820742>.
- Bixler, R., & D'Mello, S. (2016). Automatic gaze-based user-independent detection of mind wandering during computerized reading. *User Modeling and User-Adapted Interaction*, 26(1), 33–68. <https://doi.org/10.1007/s11257-015-9167-1>
- Bixler, R., & D'Mello, S. (2014). Toward fully automated person-independent detection of mind wandering. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 8538, 37–48. https://doi.org/10.1007/978-3-319-08786-3_4
- Blanchard, N., Bixler, R., Joyce, T., & D'mello, S. (2014). Automated Physiological-Based Detection of Mind Wandering during Learning Cognition, Affect, and Learning View project Cross-domain Application of Multimodal Models to Understand Real-world Performance View project. https://doi.org/10.1007/978-3-319-07221-0_7
- Brouwer, G. J., Van Ee, R., & Schwarzbach, J. (2005). *Behavioral/Systems/Cognitive Activation in Visual Cortex Correlates with the Awareness of Stereoscopic Depth*. <https://doi.org/10.1523/JNEUROSCI.2408-05.2005>
- Chen, S., & Epps, J. (2013). Automatic classification of eye activity for cognitive load measurement with emotion interference. *Computer Methods and Programs in Biomedicine*, 110(2), 111–124. <https://doi.org/10.1016/j.cmpb.2012.10.021>
- Chermahini, S. A., & Hommel, B. (2010). The (b)link between creativity and dopamine: Spontaneous eye blink rates predict and dissociate divergent and convergent thinking. *Cognition*, 115(3), 458–465. <https://doi.org/10.1016/j.cognition.2010.03.007>
- Christoff, K., Gordon, A. M., Smallwood, J., Smith, R., & Schooler, J. W. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proceedings of the National Academy of Sciences of the United States of America*, 106(21), 8719–8724. <https://doi.org/10.1073/pnas.0900234106>
- D'Mello, S., Dieterle, E., & Duckworth, A. (2017). Advanced, Analytic, Automated (AAA) Measurement of Engagement During Learning. *Educational Psychologist*, 52(2), 104–123. <https://doi.org/10.1080/00461520.2017.1281747>
- D'Mello, S., Kopp, K., Bixler, R., & Bosch, N. (2016). Attending to attention: Detecting and combating Mind wandering during computerized reading. *Conference on Human Factors in Computing Systems - Proceedings, 07–12-May*, 1661–1669. <https://doi.org/10.1145/2851581.2892329>
- Faber, M., Bixler, R., & D'Mello, S. K. (2018). An automated behavioral measure of mind wandering during computerized reading. *Behavior Research Methods*, 50(1), 134–150. <https://doi.org/10.3758/s13428-017-0857-y>
- Faber, M., Krasich, K., Bixler, R. E., Brockmole, J. R., & D'Mello, S. K. (2020). The Eye-Mind Wandering Link: Identifying Gaze Indices of Mind Wandering Across Tasks. *Journal of Experimental Psychology: Human Perception and Performance*, 2020(10), 1201–1221. <https://doi.org/10.1037/xhp0000743>
- Fatt, I., & Weissman, B. (2013). *Physiology of the Eye. An Introduction to the Vegetative Functions* ((2nd ed.)). Butterworth-Heinemann.
- Fogarty, C., & Stern, J. A. (1989). Eye movements and blinks: Their relationship to higher cognitive processes. *International Journal of Psychophysiology*, 8(1), 35–42. [https://doi.org/10.1016/0167-8760\(89\)90017-2](https://doi.org/10.1016/0167-8760(89)90017-2)
- Frank, D. J., Nara, B., Zavagnin, M., Touron, D. R., & Kane, M. J. (2015). Validating older adults' reports of less mind-wandering: An examination of eye movements and dispositional influences. *Psychology and Aging*, 30(2), 266–278. <https://doi.org/10.1037/pag0000031>
- Freeman, J. B., & Dale, R. (2013). Assessing bimodality to detect the presence of a dual cognitive process. *Behavior Research Methods*, 45(1), 83–97. <https://doi.org/10.3758/s13428-012-0225-x>
- Geng, J. J., Ruff, C. C., & Driver, J. (2009). Saccades to a remembered location elicit spatially specific activation in human retinotopic visual cortex. *Journal of Cognitive Neuroscience*, 21(2), 230–245. <https://doi.org/10.1162/jocn.2008.21025>
- Grandchamp, R., Braboszcz, C., & Delorme, A. (2014). Oculometric variations during mind wandering. *Frontiers in Psychology*, 5(FEB), 31. <https://doi.org/10.3389/fpsyg.2014.00031>
- Guittton, D., Simard, R., & Codere, F. (1991). Upper eyelid movements measured with a search coil during blinks and vertical saccades. *Investigative Ophthalmology and Visual Science*, 32(13), 3298–3305.
- Hartigan, J. A., & Hartigan, P. M. (1985). The Dip Test of Unimodality. *The Annals of Statistics*, 13(1), 70–84. <https://doi.org/10.1214/aos/1176346577>
- Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & Weijer, J. Van De. (2011). *Eye Tracking: A comprehensive guide to methods and measures* (p. 560). https://books.google.com/books?hl=en&lr=&id=5rIDPV1EoLUC&oi=fnd&pg=PR12&dq=Eye+Tracking:+a+Comprehensive+Guide+to+Methods+and+Measures&ots=w5FUZuMrl&sig=4VNy9FvmRH2XEgPMBko_5FipApU
- Hoppe, D., Helfmann, S., & Rothkopf, C. A. (2018). Humans quickly learn to blink strategically in response to environmental task demands. *Proceedings of the National Academy of Sciences of the United States of America*, 115(9), 2246–2251. <https://doi.org/10.1073/pnas.1714220115>
- Huette, S., Mathis, A., & Graesser, A. (2016). Blink durations reflect mind wandering during reading. *CogSci*. <https://pdfs.semanticscholar.org/fba2/314dea3944723ddc0348dc41a6e823dd5410.pdf>
- Hutt, S., Mills, C., Bosch, N., Krasich, K., Brockmole, J., & D'mello, S. (2017). Out of the Fr-"Eye"-ing Pan: Towards gaze-based models of attention during learning with technology in the classroom. *UMAP 2017 - Proceedings of the 25th Conference on User Modeling, Adaptation and Personalization*, 94–103. <https://doi.org/10.1145/3079628.3079669>
- Hutt, S., Mills, C., White, S., Donnelly, P. J., & D'Mello, S. K. (2016). The eyes have it: Gaze-based Detection of Mind Wandering during Learning with an Intelligent Tutoring System. *Proceedings of the 9th International Conference on Educational Data Mining*.
- Kane, M. J., Brown, L. H., McVay, J. C., Silvia, P. J., Myin-Germeys, I., & Kwapil, T. R. (2007). For whom the mind wanders, and when: An experience-sampling study of working memory and executive control in daily life. *Psychological Science*, 18(7), 614–621. <https://doi.org/10.1111/j.1467-9280.2007.01948.x>
- Killingsworth, M. A., & Gilbert, D. T. (2010). A wandering mind is an unhappy mind. *Science*, 330(6006), 932. <https://doi.org/10.1126/science.1192439>
- Krasich, K., McManus, R., Hutt, S., Faber, M., D'Mello, S. K., & Brockmole, J. R. (2018). Gaze-based signatures of mind wandering during real-world scene processing. *Journal of Experimental Psychology: General*, 147(8), 1111–1124. <https://doi.org/10.1037/xge0000411>
- Mason, M. F., Norton, M. I., Van Horn, J. D., Wegner, D. M., Grafton, S. T., & Macrae, C. N. (2007). Wandering minds: The default network and stimulus-independent thought. *Science*, 315(5810), 393–395. <https://doi.org/10.1126/science.1131295>
- Mechler, F. (2002). A direct translation into MATLAB from the original FORTRAN code of Hartigan's Subroutine DIPTST algorithm. <http://www.nicprice.net/diptest>
- Mills, C., Bixler, R., Wang, X., & D'Mello, S. K. (2016). Automatic gaze-based detection of mind wandering during narrative film comprehension. *Proceedings of the 9th International Conference on Educational Data Mining*.
- Mills, C., & D'Mello, S. (2015). Toward a Real-time (Day) Dreamcatcher: Detecting Mind Wandering Episodes During Online Reading. In *Proceedings of the 8th International Conference on Educational Data Mining* (pp. 69–76).
- Mooneyham, B. W., & Schooler, J. W. (2013). The costs and benefits of mind-wandering: A review. *Canadian Journal of Experimental Psychology*, 67(1), 11–18. <https://doi.org/10.1037/a0031569>

- Mrazek, A. J., Ihm, E. D., Molden, D. C., Mrazek, M. D., Zedelius, C. M., & Schooler, J. W. (2018). Expanding minds: Growth mindsets of self-regulation and the influences on effort and perseverance. *Journal of Experimental Social Psychology*, 79, 164–180. <https://doi.org/10.1016/j.jesp.2018.07.003>
- Murphy, C., Jefferies, E., Rueschemeyer, S. A., Sormaz, M., Wang, H. ting, Margulies, D. S., & Smallwood, J. (2018). Distant from input: Evidence of regions within the default mode network supporting perceptually-decoupled and conceptually-guided cognition. *NeuroImage*, 171, 393–401. <https://doi.org/10.1016/j.neuroimage.2018.01.017>
- Murphy, C., Wang, H. T., Konu, D., Lowndes, R., Margulies, D. S., Jefferies, E., & Smallwood, J. (2019). Modes of operation: A topographic neural gradient supporting stimulus dependent and independent cognition. *NeuroImage*, 186, 487–496. <https://doi.org/10.1016/j.neuroimage.2018.11.009>
- Nakano, T. (2015). Blink-related dynamic switching between internal and external orienting networks while viewing videos. *Neuroscience Research*, 96, 54–58. <https://doi.org/10.1016/j.neures.2015.02.010>
- Nakano, T., Kato, M., Usuke, M., Itoi, S., & Shigeru, K. (2013). Blink-related momentary activation of the default mode network while viewing videos. *Proceedings of the National Academy of Sciences*, 110(2), 702–706. <https://doi.org/10.1073/pnas.1214804110>
- Qin, P., & Northoff, G. (2011). How is our self related to midline regions and the default-mode network? *NeuroImage*, 57(3), 1221–1233. <https://doi.org/10.1016/j.neuroimage.2011.05.028>
- R Core Team. (2020). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. <https://www.R-project.org/>.
- Raichle, M. E. (2015). The Brain's Default Mode Network. *Annual Review of Neuroscience*, 38(1), 433–447. <https://doi.org/10.1146/annurev-neuro-071013-014030>
- Randall, J. G., Oswald, F. L., & Beier, M. E. (2014). Mind-wandering, cognition, and performance: A theory-driven meta-analysis of attention regulation. *Psychological Bulletin*, 140(6), 1411–1431. <https://doi.org/10.1037/a0037428>
- Schad, D. J., Nuthmann, A., & Engbert, R. (2012). Your mind wanders weakly, your mind wanders deeply: Objective measures reveal mindless reading at different levels. *Cognition*, 125(2), 179–194. <https://doi.org/10.1016/j.cognition.2012.07.004>
- Schooler, J. W., Reichle, E. D., & Halpern, D. V. (2004). Thinking and Seeing: Visual Metacognition in Adults and Children. In D. T. Levin (Ed.), *Zoning out while reading: Evidence for dissociations between experience and metaconsciousness* (pp. 203–226). MIT Press.
- Schooler, J. W., Smallwood, J., Christoff, K., Handy, T. C., Reichle, E. D., & Sayette, M. A. (2011). Meta-awareness, perceptual decoupling and the wandering mind. *Trends in Cognitive Sciences*, 15(7), 319–326. <https://doi.org/10.1016/j.tics.2011.05.006>
- Seli, P., Carriere, J. S. A., Levene, M., & Smilek, D. (2013). How few and far between? Examining the effects of probe rate on self-reported mind wandering. *Frontiers in Psychology*, 4(JUL). <https://doi.org/10.3389/fpsyg.2013.00430>
- Siegle, G. J., Ichikawa, N., & Steinhauer, S. (2008). Blink before and after you think: Blinks occur prior to and following cognitive load indexed by pupillary responses. *Psychophysiology*, 45(5), 679–687. <https://doi.org/10.1111/j.1469-8986.2008.00681.x>
- Singh, K. D., & Fawcett, I. P. (2008). Transient and linearly graded deactivation of the human default-mode network by a visual detection task. *NeuroImage*, 41(1), 100–112. <https://doi.org/10.1016/j.neuroimage.2008.01.051>
- Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin*, 132(6), 946–958. <https://doi.org/10.1037/0033-2909.132.6.946>
- Smilek, D., Carriere, J. S. A., & Cheyne, J. A. (2010). Out of mind, out of sight: Eye blinking as indicator and embodiment of mind wandering. *Psychological Science : A Journal of the American Psychological Society / APS*, 21(6), 786–789. <https://doi.org/10.1177/0956797610368063>
- Spreng, R. N., & Grady, C. L. (2010). Patterns of brain activity supporting autobiographical memory, prospection, and theory of mind, and their relationship to the default mode network. *Journal of Cognitive Neuroscience*, 22(6), 1112–1123. <https://doi.org/10.1162/jocn.2009.21282>
- Uzzaman, S., & Joordens, S. (2011). The eyes know what you are thinking: Eye movements as an objective measure of mind wandering. *Consciousness and Cognition*, 20(4), 1882–1886. <https://doi.org/10.1016/j.concog.2011.09.010>
- Van Orden, K. F., Limbert, W., Makeig, S., & Jung, T. P. (2001). Eye activity correlates of workload during a visuospatial memory task. *Human Factors*, 43(1), 111–121. <https://doi.org/10.1518/001872001775992570>
- Vuong, Q. H. (1989). Likelihood Ratio Tests for Model Selection and Non-Nested Hypotheses. *Econometrica*, 57(2), 307. <https://doi.org/10.2307/1912557>
- Walcher, S., Körner, C., & Benedek, M. (2017). Looking for ideas: Eye behavior during goal-directed internally focused cognition. *Consciousness and Cognition*, 53, 165–175. <https://doi.org/10.1016/j.concog.2017.06.009>
- Weinstein, Y. (2018). Mind-wandering, how do I measure thee with probes? Let me count the ways. *Behavior Research Methods*, 50(2), 642–661. <https://doi.org/10.3758/s13428-017-0891-9>
- Zeileis, A., Kleiber, C., & Jackman, S. (2007). *Regression models for count data in R*. <https://scholar.google.com/ftp://mirror.csclub.uwaterloo.ca/CRAN/web/packages/pscl/pscl.pdf>.
- Zhang, H., Anderson, N. C., & Miller, K. F. (2021). Refixation patterns of mind-wandering during real-world scene perception. *Journal of Experimental Psychology: Human Perception and Performance*, 47(1), 36–52. <https://doi.org/10.1037/xhp0000877>