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Gaze-Based Signatures of Mind Wandering During Real-World Scene Processing

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Physiological limitations on the visual system require gaze to move from location to location to extract the most relevant information within a scene. Therefore, gaze provides a real-time index of the information-processing priorities of the visual system. We investigated gaze allocation during mind wandering (MW), a state where cognitive priorities shift from processing task-relevant external stimuli (i.e., the visual world) to task-irrelevant internal thoughts. In both a main study and a replication, we recorded the eye movements of college-aged adults who studied images of urban scenes and responded to pseudorandom thought probes on whether they were mind wandering or attentively viewing at the time of the probe. Probe-caught MW was associated with fewer and longer fixations, greater fixation dispersion, and more frequent eyeblinks (only observed in the main study) relative to periods of attentive scene viewing. These findings demonstrate that gaze indices typically considered to represent greater engagement with scene processing (e.g., longer fixations) can also indicate MW. In this way, the current work exhibits a need for empirical investigations and computational models of gaze control to account for MW for a more accurate representation of the moment-to-moment information-processing priorities of the visual system.

Keywords: gaze control, scene perception, mind wandering, eye tracking

Vision is crucial for many everyday activities, such as reading and driving. Despite the importance of vision in our daily lives, we are limited in our moment-to-moment ability to obtain task-relevant information from the visual world. Physiological limitations on visual acuity along with parallel cognitive limitations on attention and memory force us to shift our eye gaze from location to location to construct a detailed and timely representation of the surrounding environment. The manner in which eye gaze is allocated within a scene, therefore, provides a real-time index of the information-processing priorities of the visual system and the strategies used by the mind and brain to sample information in service of ongoing goals. Because of this critical link between the eye, mind, and brain, over a century of research has used eye-tracking methods to investigate how people view their world (Wade & Tatler, 2005).

The control of gaze, and the resulting acquisition of visual information, is determined by two fundamental (but not entirely inseparable) decision processes. First, we must determine where we should look and, second, we must decide how long we should look there. This cycle of "where-and-when" decisions repeats about 3–4 times per second as we view our surroundings and is influenced by a long and varied list of factors. For instance, in the context of scene processing, fixation point selection has been associated with local image statistics (e.g., Krieger, Rentschler,

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Hauske, Schill, & Zetzsche, 2000; Mannan, Ruddock, & Wooding, 1996; Parkhurst, Law, & Niebur, 2002), measures of visual salience and contiguity (e.g., Borji & Itti, 2013; Itti, Koch, & Niebur, 1998; Judd, Durand, & Torralba, 2012), short-term assessments of semantic interest (e.g., Buswell, 1935; Loftus & Mackworth, 1978), momentary task goals (e.g., Land & Hayhoe, 2001; Land & Lee, 1994; Yarbus, 1967), long-term schematic knowledge of scene structure (e.g., Mandler & Johnson, 1977; Shinoda, Hayhoe, & Shrivastava, 2001; Võ & Henderson, 2009), and episodic memory for previously viewed scenes (e.g., Brockmole & Henderson, 2006; Castelhano & Henderson, 2005). When considered in concert, these factors indicate what information in a scene is most likely to be relevant at a particular moment in time. Meanwhile, variation in fixation durations often reflects the quality of the available visual information (e.g., Najemnik & Geisler, 2005, 2009), the ease with which objects can be recognized and understood in context (e.g., Becker, Pashler, & Lubin, 2007; Bonitz & Gordon, 2008; Castelhano & Henderson, 2007; Henderson & Castelhano, 2005; Hollingworth, 2006; Underwood, Templeman, Lamming, & Foulsham, 2008), and the relevant goals and strategies of the observer (e.g., Neider & Zelinsky, 2006). Based on these effects, it is broadly thought that fixation durations reflect the effort needed to extract meaning from the regions of a scene that are selected for viewing.

Researchers have recently turned their efforts toward modeling how these factors, and their interactions, contribute to gaze control and, hence, the overt allocation of attention (e.g., Borji & Itti, 2013; Itti et al., 1998; Judd et al., 2012; Mackay, Cerf, & Koch, 2012; Nuthmann, Smith, Engbert, & Henderson, 2010; Tatler, Brockmole, & Carpenter, 2017; Torralba, Oliva, Castelhano, & Henderson, 2006; Unema, Pannasch, Joos, & Velichkovsky, 2005; Wischnewski, Belardinelli, Schneider, & Steil, 2010). A fundamental, and often unspoken, assumption underlies this work: namely that people consistently and appropriately pay attention to their visual surroundings in service of task goals. However, our minds are not always engaged in task-relevant activities. People often fall prey to what is known as zoning out or *mind wandering* (MW) where attention drifts away from task-related thoughts to unrelated thoughts, such as lunch, childcare, or an upcoming trip. One large-scale study showed that among a group of 5,000 individuals from 83 countries working in 86 different occupations, people reported that around 47% of their thoughts were considered to be MW (Killingsworth & Gilbert, 2010), a rate substantiated in many laboratory-based studies that obtained MW rates in the 20–50% range depending on the nature of the task (see Smallwood & Schooler, 2015 for review). The negative behavioral effects of MW are pervasive; a recent meta-analysis of 88 adult samples showed clear negative correlations between MW and task performance (Randall, Oswald, & Beier, 2014). Given the high prevalence and consequence of MW, investigations into gaze control during scene processing without reference to MW discounts a substantial portion of daily life and task performance, thus, obfuscating a comprehensive understanding of how the mind and brain sample the visual world. It is therefore critical that we begin to establish the relationship between eye movements and MW during visual tasks such as scene viewing.

MW can essentially be construed as a shift in one's attentional priorities from external stimuli to internal thoughts (Smallwood & Schooler, 2006). For instance, the visual P1 ERP component, which reflects early cortical processing of visual stimuli, decreases during MW in comparison to on-task attentional focus (Baird, Smallwood, Lutz, & Schooler, 2014; Kam et al., 2011; Smallwood, Beach, Schooler, & Handy, 2008). Conversely, activity within the default-mode network—the network of brain regions within the medial surface of the cortex that is active during stimulus-independent, internally focused thoughts (Buckner, Andrews-Hanna, & Schacter, 2008)—increases during MW (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Mason et al., 2007). As the mind decouples from processing external stimuli, the attentional priorities of the visual system are likely to change, which may result in eye gaze patterns characteristic of MW. Specifically identifying gaze patterns unique to MW will reveal how the visual system reprioritizes external information when thoughts are directed inward.

The possibility that gaze patterns during scene viewing may change during MW is supported by recent studies showing that certain aspects of gaze are correlated with MW during reading. For example, MW has been consistently associated with fewer fixations and longer fixation durations compared with periods of normal reading (Faber, Bixler, & D'Mello, 2017; Reichle, Reineberg, & Schooler, 2010; Uzzaman & Joordens, 2011). Some evidence also indicates that MW may be associated with more frequent eyeblinks (Smilek, Carriere, & Cheyne, 2010; but also see Faber et al., 2017; Uzzaman & Joordens, 2011). Although correlational, these findings are consistent with a decoupling of gaze from the processing of external stimuli—fewer regions are sampled and incoming information is physically and cognitively blocked through frequent eyeblinks (Gawne & Martin, 2000; Irwin, 2014; Thomas & Irwin, 2006; Volkmann, 1986; Volkmann, Riggs, & Moore, 1980).

It does not necessarily follow, however, that findings from reading will generalize to other tasks. Compared with the scale, variability, and density of information in the visual world at-large, reading involves a relatively sparse visual context that prescribes specific gaze patterns. The cognitive demands associated with scene viewing and reading, therefore, vary considerably (Rayner, 2009; Rayner, Li, Williams, Cave, & Well, 2007; Rayner, Smith, Malcolm, & Henderson, 2009). As such, when attempting to account for the mechanisms underlying gaze control, reading and scene processing are modeled separately (Engbert, Nuthmann, Richter, & Kliegl, 2005; Mackay et al., 2012; Nuthmann et al., 2010; Reichle, Pollatsek, Fisher, & Rayner, 1998; Tatler et al., 2017; Torralba et al., 2006; Unema et al., 2005; Wischnewski et al., 2010). Therefore, despite suggestive evidence from reading tasks, it remains unknown how MW and gaze control may be related during scene viewing, which motivated the present study.

We considered several aspects of gaze control in this study, starting with the number and duration of fixations. These temporal aspects of gaze control are associated with MW during reading (Faber et al., 2017; Reichle et al., 2010; Smilek et al., 2010; Uzzaman & Joordens, 2011), and it is natural to first ask if they similarly index MW during scene viewing. Next, we assessed fixation point selection. Because shifts in gaze during scene viewing are far less constrained than those during reading (Rayner, 2009), scene viewing provides a rich context within which possible associations between MW and the spatial aspects of gaze can be determined. Lastly, we analyzed the frequency of eyeblinks to assess the relationship between the cognitive factors of gaze control and MW in scene viewing (Gawne & Martin, 2000; Irwin, 2014; Nakano, Yamamoto, Kitajo, Takahashi, & Kitazawa, 2009; Thomas & Irwin, 2006; Volkmann, 1986; Volkmann et al., 1980).

To contrast gaze control when people mind wander versus attend to scenes, we asked participants to study a series of digitized photographs of urban scenes for a subsequent recognition test (see Figure 1). We measured MW with pseudorandomly distributed *thought probes* that prompted participants to report whether they were fully attending to the scene or mind wandering at the time of the probe (Smallwood & Schooler, 2006). Eye movements were recorded and used to compare gaze patterns during reported incidents of MW to those of attentive viewing. We focused on global aspects of gaze control that are independent of scene content to uncover relatively content-free shifts in occulomotor variables that

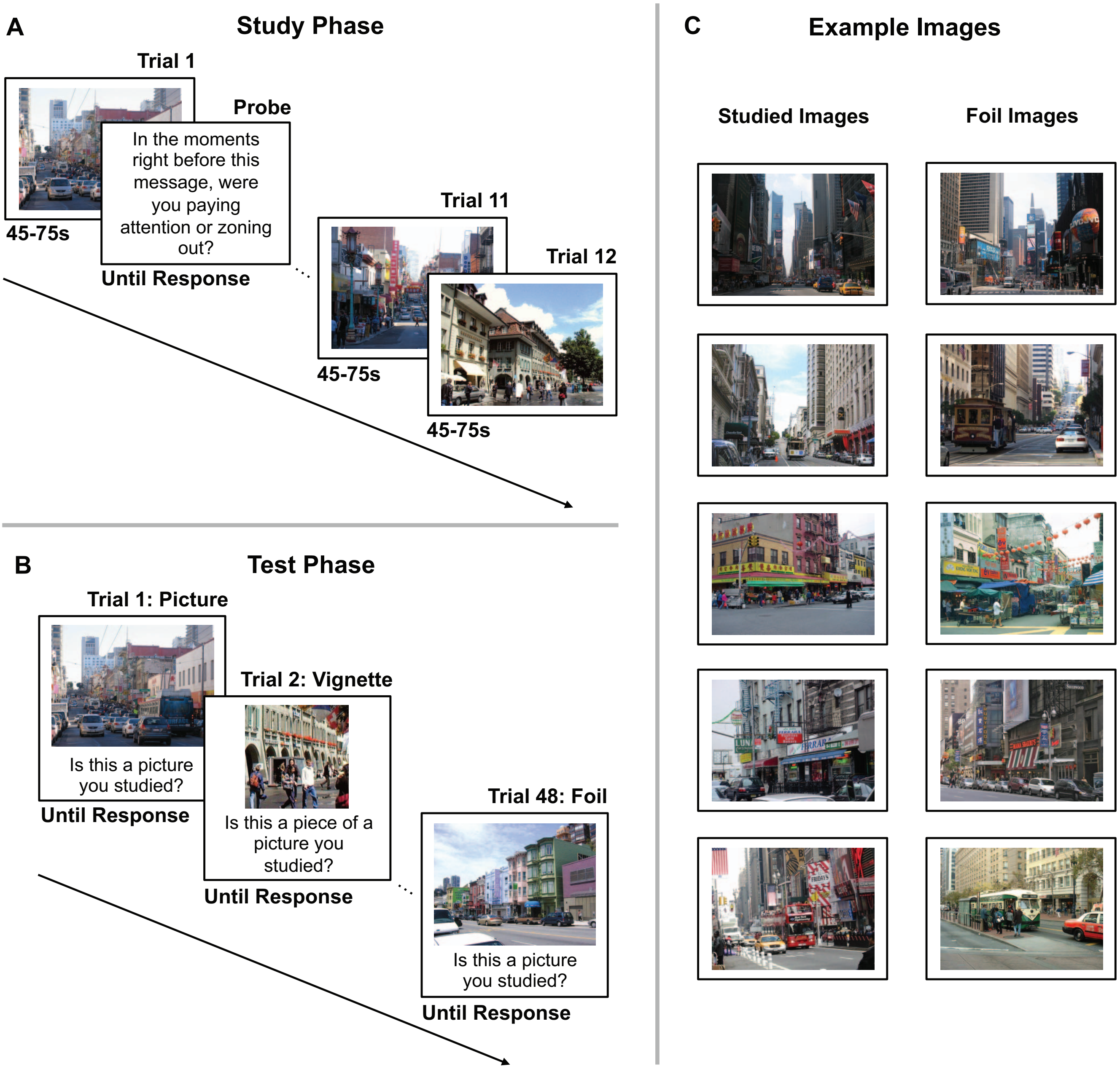

Figure 1. (A) Example trial sequence for the Study Phase. In this example, Trial 1 is a probe trial where participants are asked to report whether they are paying attention or "zoning out," a colloquial term used for mind wandering (MW). Trials 11 and 12 are no-probe trials. (B) Example trial sequence for the Test Phase. In this example, Trial 1 depicts a studied image, Trial 2 depicts a vignette extracted from a study image, and Trial 48 depicts a full sized foil image. (C) Example pictures of studied and foil images. See the online article for the color version of this figure.

could be used to predict the moment-to-moment prioritization of the visual system across varying viewing scenarios. This approach could facilitate the development of emerging initiatives aimed at implementing objective oculomotor determinants of MW to complement self-reports (e.g., Faber et al., 2017). Following the scene study phase, participants were tested on their memory using a two-alternative forced-choice recognition task that contained the 12 studied images, 12 unstudied images (foils), 12 vignettes extracted from the study images, and 12 vignettes extracted from the full size foils. Images were presented in a random order.

Method

Participants

We established an a priori target sample size of 50 participants from a private, selective, Midwest university. To compensate for potential cancellations or technical difficulties, we overrecruited participants by 10%. This strategy yielded a final sample of 51 participants (M_{age} = 19 years, *SD* = 1.1 years, female = 37). Informed consent was obtained from each participant, and the University Institutional Review Board approved all experimental procedures. Participants were compensated with course credit.

Stimuli and Apparatus

The stimuli consisted of 24 digitized color photographs of real-world urban scenes displayed either in full at a resolution of 800 × 600 pixels or in part by extracting a smaller 200 × 200 pixel portion of the original images (vignettes). All stimuli were presented in 32-bit color on a 20-in. CRT monitor with a screen refresh rate of 85 Hz and a resolution of 1,024 × 768.

Participants' eye movements were sampled at a rate of 1,000 Hz using an EyeLink 2K tower mounted eye tracking system (SR Research, Inc.). A chin and forehead rest was used to maintain a viewing distance of 80 cm. The eye tracker was calibrated using a 9-point calibration at the beginning of the study. A 1-point calibration was used before each trial to correct for subtle drift in the eye tracker signal over time. Responses were registered by pressing one of two keys on a standard QWERTY keyboard.

Design and Procedure

The study was divided into two phases. The first phase was the *study phase* (Figure 1A) and was composed of 12 trials. On each trial, participants were shown a full scene that they were to memorize for a test administered after the study phase. All participants viewed the same 12 scenes in a different pseudorandom order. Each scene was presented for a randomly selected duration between 45 and 75 s (M = 59.96 s, *SD* = 8.49 s). Eight trials were pseudorandomly selected to include a thought probe: After the scene was cleared from the display, a text prompt asked participants to report whether they were mind wandering or paying attention at that moment. Specifically, participants were asked, "In the moments right before this message, were you paying attention to the picture or were you zoning out?" (Schooler, Reichle, & Halpern, 2004). *Zoning out* was used as a more colloquial term for MW and defined for participants at the start of the study as the act of "looking at the picture but thinking of something else entirely" unrelated to the scenes' content. Participants responded using a key press, which also initiated the next trial (on the four trials without a thought probe, the next trial began automatically).

The study phase was immediately followed by the *test phase* (Figure 1B). Participants completed a self-paced, two-alternative forced-choice recognition task that contained the 12 studied images, 12 unstudied images (foils), 12 vignettes extracted from the study images, and 12 vignettes extracted from the foils. To make the memory test nontrivial, study and foil images were subjectively matched in terms of location (e.g., city, architectural style, etc.), perspective (e.g., skylines, street views, etc.), and content (e.g., shop fronts, crowds, roadways, etc.). Examples are illustrated in Figure 1C. Stimuli were presented in a different random order for each participant. Eye movements were not recorded during the test phase.

Results

The results are divided into three sections. First, we discuss the frequency of reported MW. Then we validate these reports by demonstrating a negative relationship between MW and memory test performance. Finally, to address the primary research question, we discuss eye gaze behavior and its relationship with MW.

Incidence of MW and Correlations With Memory

On average, participants reported MW on 27% of probes (*SD* = 22%), with 11 participants reporting no MW and 1 participant reporting MW for all 8 probes. This rate of MW is within the range of rates reported during both laboratory studies and experience sampling studies in the real world (see Smallwood & Schooler, 2015 for review).

Memory performance for full-size images (M = 98%, *SD* = 4%) and vignettes (M = 82%, *SD* = 9%) were correlated, Spearman's $\rho = .613$, $p < .001$, and, thus, were combined to investigate the relationship between MW and scene memory. MW was negatively correlated with overall memory test performance (M = 90%, *SD* = 6%), Spearman's $\rho = -.306$, $p = .029$. An interesting finding was that MW was associated with lower test performance for foil images (M = 88%, *SD* = 8%), Spearman's $\rho = -.294$, $p = .036$, rather than studied images (M = 92%, *SD* = 7%), Spearman's $\rho = -.139$, $p = .332$. These findings suggest that MW might impair memory for visual detail even when overall gist memory remains intact and are consistent with accounts showing that MW is associated with a decoupling from external stimuli, whereby external visual information is deprioritized (see Schooler et al., 2011 for review), resulting in lower task performance (Mills, Graesser, Risko, & D'Mello, 2017).

Relationship Between MW and Gaze

We tested our main hypothesis that MW is associated with changes in gaze allocation that reflect a shift in information-prioritization of the visual system. Out of 612 total trials, we analyzed the 408 trials that included a thought probe. We compared gaze patterns on trials where participants reported MW (109 trials) to trials where participants reported attentive viewing of the scenes (299 trials). The dependent measures included the number, duration, and dispersion of fixations, the amplitude of saccades, and the frequency of eyeblinks. Saccades were operationally defined as changes in recorded fixation position that exceeded 0.2° with either a velocity that exceeded 30°/s or an acceleration that exceeded 9,500°/s^2. For fixation-based analyses, fixations shorter than 50 ms (2% of fixations) and longer than 10,000 ms (<.01% of fixations) were excluded.

Each trial was divided into nine 5 s time windows with respect to the onset of the thought probe (i.e., 45–40 s before probe onset, 40–35 s before probe onset, etc.), which allowed us to study gaze-based correlates of MW over time. Within each window, average values for each gaze variable were computed. Using the *lme4* package in R (Bates, Mächler, Bolker, & Walker, 2015), we conducted mixed-effect linear regression analyses that modeled each gaze variable as a *probe response* (two levels: paying attention [reference group] and MW) by *time window* (nine levels with 5–0 s window as the reference group) interaction with *participant* as a random effect. *Image* (12 levels) was included as a fixed-effect covariate, as was *image viewing time* to account for content-specific shifts in eye movement patterns that are known to emerge over the course of viewing. For instance, gaze is often distributed broadly at first to extract the global spatial layout of the scene (e.g., Karpov, Luria, & Yarbuss, 1968), before shifting to focal processing that is apt for object identification (Antes, 1974; Pannasch, Helmert, Roth, Herbold, & Walter, 2008; Tatler, Gilchrist, & Rusted, 2003; Unema et al., 2005; Velichkovsky, Joos, Helmert, & Pannasch, 2005).

Reported unstandardized coefficients (*B*) indicate the predicted change in the dependent variable for each unit increase in the predictor variables. Significance testing was conducted using two-tailed tests with α set to .05 (Bonferroni corrections were used on all post hoc tests at $p < .006$; i.e., .05/9 time windows). Chi-square ratios and *p* values are reported using the *car* package in R (Fox & Weisberg, 2011) using a Type II sum of squares to investigate the main effects of MW controlling for covariates. Coefficients and test statistics for each predictor are reported in the Appendix. Test statistics most relevant to assessing the relationship between eye movements and MW are reported in Table 1 and illustrated in Figure 2. In the presence of a significant probe response by time window interaction, only the interaction is reported and interpreted.

Number of fixations. Reports of MW were associated with fewer fixations ($M = 11.5$ fixations per time window, $SD = 3.95$) compared with reports of attentive viewing ($M = 13.1$ fixations per time window, $SD = 3.33$), an effect that varied across time windows, $\chi^2(8) = 23.4$, $p = .016$. Participants who reported MW made fewer fixations as time elapsed in the trial, with significantly detectable differences occurring as early as 20–25 s before the MW report.

Fixation durations. MW was associated with longer fixation durations ($M = 357$ ms, $SD = 399$ ms) compared with reports of attentive viewing ($M = 320$ ms, $SD = 250$ ms), an effect that varied across time windows, $\chi^2(8) = 18.9$, $p = .015$, in that MW was associated with significantly longer fixation durations as time elapsed in the trial. Post hoc analyses indicated detectable differences in fixation duration as early as 10–15 s before the MW report.

Saccade amplitude. Saccade amplitude (i.e., the distance between two consecutive fixations) was similar across trials with reported MW ($M = 2.73°$, $SD = 2.93°$) and attentive viewing ($M = 2.48°$, $SD = 2.49°$), $\chi^2(1) = .822$, $p = .365$. There was a marginal probe response and time window interaction, $\chi^2(8) = 13.5$, $p = .095$; however, post hoc analyses revealed no significant differences between MW and attentive viewing.

Fixation dispersion. Fixation dispersion is a measure of the spatial extent or spread of fixations. It is computed as the root mean square of the euclidean distance from each fixation to the average position of all fixations. Values are reported on a 0–1 scale with higher values indicating greater dispersion of fixations across the scenes. Reports of MW were associated with greater fixation dispersion ($M = .242$ per time window, $SD = .140$) compared with reports of attentive viewing ($M = .225$ per time window, $SD = .113$), although this relationship was marginal, $\chi^2(1) = 2.83$, $p = .093$, $B = .025$, $SE = .014$. There was also a marginal probe response by time window interaction, $\chi^2(8) = 13.4$, $p = .099$. Post hoc analyses indicated that fixation dispersion was significantly greater on MW trials within the 10–5 s time window and trending at the 5–0 s time window. Hence, fixation locations may become more dispersed about 5–10 s before reported MW.

Number of blinks. Reports of MW were associated with more eyeblinks ($M = 1.98$ blinks per time window, $SD = 1.65$) compared with reports of attentive viewing ($M = 1.77$ blinks per time window, $SD = 1.51$), $\chi^2(1) = 9.54$, $p = .002$, $B = .151$, $SE = .134$, an effect that was similar across time windows, $\chi^2(8) = 4.70$, $p = .789$. Thus, MW may be associated with higher blink rates, although this effect has less temporal precision than aforementioned aspects of gaze control.

Replication

To verify the eye movement patterns associated with MW, we performed a conceptual replication of our main study. We established an a priori target sample size of 40 participants from the same participant population as Experiment 1. Overrecruitment resulted in a final sample of 41 participants ($M_{\text{age}} = 21$ years, $SD = 1.9$ years, female = 30). Participants viewed six sequentially presented images of urban scenes for 60 s each. Rather than divide the experiment into discrete trials, scenes were presented contiguously. Thought probes were presented at pseudorandom intervals of 90–120 s over the course of the scene viewing task so that each participant received three thought probes total. On average, participants reported MW on 47% of probes ($SD = 50\%$).

As in the main experiment, eye movements were parsed into 5 s time windows with respect to the onset of the thought probe. The contiguous presentation of scenes coupled with the revised scene presentation times, limited our analyses to the 30 s before probe onset. For analysis, we used the *lme4* package in R (Bates et al., 2015) to compute linear mixed-effect regression models for each gaze variable in the same manner as the main experiment, with two changes. First, given that we were more restricted in terms of the time windows available for analysis, we only explored main effects and, thus, we did not include the probe response by time window interaction in the models. Second, because participants completed this scene task within a battery of other randomly ordered tasks falling outside the scope of this report (e.g., listening, reading, and problem solving), we included *task order* as a categorical fixed-effect covariate in the models.

Table 1
Means, SDs, Coefficients, and Test Statistics for the Main Experiment

Time window (s)	Mind wandering M (SD)	Attentive viewing M (SD)	B	2.5% CI	97.5% CI	p-value
Number of fixations						
45–40	12.6 (3.68)	13.5 (3.26)	−.698	−1.43	.031	.064
40–35	12.4 (3.43)	13.5 (3.18)	−.790	−1.48	−.100	.026
35–30	12.1 (3.85)	13.2 (3.24)	−.820	−1.55	−.087	.029
30–25	11.8 (3.89)	13.1 (3.16)	−.683	−1.41	.046	.064
25–20	11.5 (3.91)	13.2 (3.29)	−1.12	−1.85	−.385	.002*
20–15	11.3 (3.72)	13.1 (3.44)	−.976	−1.73	−.222	.011
15–10	10.8 (3.96)	12.9 (3.38)	−1.66	−2.43	−.891	<.001*
10–5	10.7 (4.11)	12.9 (4.32)	−1.81	−2.60	−1.03	<.001*
5–0	10.3 (4.45)	12.4 (3.53)	−1.59	−2.41	−.779	<.001*
Fixation duration (milliseconds)						
45–40	329 (324)	311 (236)	52.5	.098	105	.051
40–35	327 (308)	313 (250)	28.3	−64.2	121	.554
35–30	335 (351)	315 (230)	80.8	2.14	159	.046
30–25	342 (338)	319 (252)	50.5	−34.5	135	.246
25–20	368 (436)	323 (263)	122	−4.76	248	.059
20–15	359 (365)	317 (254)	57.5	−39.3	154	.246
15–10	381 (474)	325 (256)	173	81.0	265	<.001*
10–5	392 (466)	326 (260)	154	75.7	233	<.001*
5–0	391 (511)	332 (250)	225	94.3	355	.001*
Saccade amplitude (deg visual angle)						
45–40	2.81 (3.05)	2.55 (2.41)	.174	−.054	.402	.140
40–35	2.86 (3.08)	2.52 (2.52)	.310	.071	.547	.011
35–30	2.68 (2.78)	2.53 (2.62)	−.087	−.388	.216	.570
30–25	2.61 (2.66)	2.45 (2.42)	−.093	−.357	.170	.493
25–20	2.77 (2.86)	2.44 (2.52)	.205	−.036	.445	.095
20–15	2.62 (2.64)	2.46 (2.47)	.083	−.162	.327	.512
15–10	2.75 (3.08)	2.42 (2.44)	.356	.066	.644	.016
10–5	2.80 (3.13)	2.43 (2.50)	.185	−.048	.417	.123
5–0	2.69 (3.08)	2.49 (2.51)	−.089	−.402	.222	.579
Fixation dispersion [0 to 1]						
45–40	.232 (.139)	.219 (.088)	.013	−.010	.036	.284
40–35	.224 (.136)	.223 (.113)	−.001	−.027	.025	.940
35–30	.227 (.123)	.238 (.124)	−.008	−.036	.019	.560
30–25	.230 (.097)	.218 (.115)	.012	−.013	.037	.348
25–20	.249 (.143)	.220 (.115)	.021	−.008	.049	.150
20–15	.240 (.136)	.234 (.131)	−.005	−.036	.025	.745
15–10	.253 (.150)	.230 (.112)	.022	−.006	.050	.123
10–5	.261 (.144)	.219 (.115)	.044	.018	.070	.002*
5–0	.262 (.177)	.229 (.103)	.032	.004	.061	.030
Number of blinks						
45–40	1.92 (1.71)	1.61 (1.35)	.296	.015	.587	.042
40–35	1.96 (1.64)	1.65 (1.59)	.200	−.113	.511	.217
35–30	1.97 (1.47)	1.76 (1.55)	.180	−.097	.456	.210
30–25	1.92 (1.76)	1.84 (1.56)	.002	−.287	.291	.989
25–20	2.09 (1.71)	1.76 (1.54)	.254	−.060	.568	.119
20–15	2.06 (1.83)	1.81 (1.52)	.132	−.160	.423	.382
15–10	1.93 (1.61)	1.82 (1.42)	.096	−.169	.362	.483
10–5	1.95 (1.61)	1.79 (1.48)	.051	−.243	.345	.735
5–0	2.06 (1.50)	1.87 (1.56)	.255	−.029	.539	.083

Note. Time window = seconds before thought probe onset; CI = confidence interval.
* Significant at $p < .006$ with Bonferroni corrections.

The main effects associated with number of fixations, fixation duration, and fixation dispersion were replicated as was the lack of an effect for saccade amplitude. Specifically, reports of MW were associated with fewer fixations ($M = 13.8$ fixations per time window, $SD = 4.83$) compared with reports of attentive viewing ($M = 16.0$, $SD = 3.51$), $\chi^2(1) = 8.58$, $p = .003$, $B = -1.16$, $SE = .394$. Reports of MW were also associated with longer fixation durations ($M = 278$ ms, $SD = 401$ ms) compared with reports of

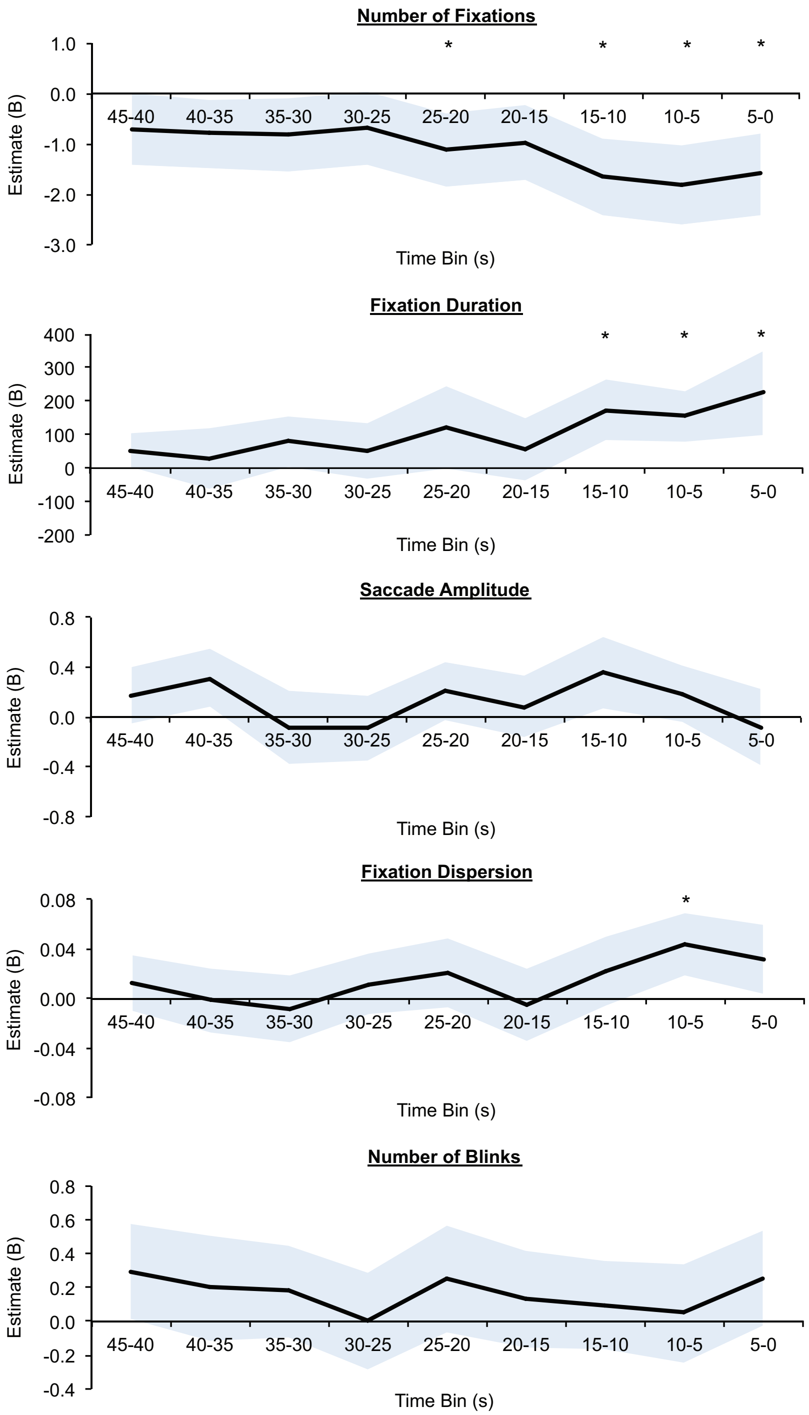

Figure 2. Unstandardized coefficients (solid black line) and 95% confidence intervals (gray shaded region) for post hoc comparisons. * Significant at $p < .006$ after Bonferroni corrections. See the online article for the color version of this figure.

attentive viewing (M = 266 ms, SD = 164 ms), $\chi^2(1) = 4.47$, p = .035, B = 35.3, SE = 16.7. As before, saccade amplitude was similar across trials with reported MW (M = 3.84, SD = 4.01) compared with attentive viewing (M = 3.82, SD = 3.88), $\chi^2(1)$ = .085, p = .770. Although the increase in fixation dispersion for MW reports was only marginal in the main experiment, reports of MW in the replication were associated with significantly greater fixation dispersion (M = .449, SD = .090) compared with reports of attentive viewing (M = .436, SD = .092), $\chi^2(1) = 8.98$, p = .003, B = .033, SE = .011. As in the main study, blink rates were numerically greater in reported cases of MW ($M = 2.03$, $SD = 1.53$) compared with attentive viewing ($M = 1.58$, $SD = 1.41$); however, this difference was not significant in the replication study, $\chi^2(1) = .292$, $p = .589$, a point we will return to in the General Discussion. Taken together, the results of the replication study provide clear evidence for important links between MW and gaze control.

General Discussion

We investigated the relationship between MW and eye gaze in the context of scene viewing. Specifically, this research focused on global aspects of gaze control that could be used to predict the moment-to-moment prioritization of the visual system across changing attentive states. The rate of reported MW echoed other laboratory and real-world investigations (Smallwood & Schooler, 2015), showing a relatively stable propensity to MW across task contexts (Kane et al., 2007; McVay, Kane, & Kwapil, 2009). MW was associated with impaired memory test performance, which supports accounts that external visual information is deprioritized during MW (e.g., Schooler et al., 2011; Smallwood et al., 2008). As such, MW was marked by gaze patterns that reflect the reprioritization of the visual system (Figure 3). For instance, MW was associated with fewer and longer fixations as early as 25–20 s before probe onset. There was also evidence that fixation locations became more dispersed during MW, with a signal detectable roughly 10–5 s before reported MW. Lastly, in the main experiment MW was associated with more frequent eyeblinks, although this finding lacked temporal precision. Collectively, the current research demonstrates gaze-based indicators of MW, which reflect real-time changes in the prioritization of the visual system.

The temporal aspects of gaze control (i.e., number and duration of fixations) were the most reliable correlates of MW during scene viewing. Our finding that MW was associated with fewer fixations and longer fixation durations complements work that has examined the associations between gaze and MW while reading (Reichle et al., 2010; Smilek et al., 2010; Uzzaman & Joordens, 2011). Although gaze control parameters often differ across reading and scene viewing (Rayner, 2009; Rayner et al., 2007, 2009), the consistent results across these two task contexts suggest a common mechanism that reprioritizes the visual system as external information is deprioritized (Baird et al., 2014; Kam et al., 2011; Smallwood et al., 2008) and attention to task-irrelevant thoughts is amplified during MW (Christoff et al., 2009; Mason et al., 2007).

The shifts in the temporal aspects of gaze control associated with MW also have broader implications for theories of scene processing. Fixation durations, for example, are often used to identify transitory priorities of the visual system (e.g., Henderson & Pierce, 2008), with longer fixations commonly associated with a more thorough evaluation of visual information because of either low quality input or high cognitive demand (e.g., Henderson & Choi, 2015; Nuthmann et al., 2010). However, this interpretation is challenged by our results because MW, a state associated with a shift of attentional priorities away from external stimuli (Baird et al., 2014; Kam et al., 2011; Smallwood et al., 2008; Smallwood & Schooler, 2006), is also associated with longer fixations. It seems puzzling, then, that a single behavioral marker (prolonged fixation durations) may indicate both greater and lesser engagement with scene processing. This apparent paradox may be resolved, however, if we reconsider the theoretical interpretation often ascribed to fixation duration.

In particular, it has recently been proposed that fixation durations may reflect the time needed for the visual system to evaluate the benefits of maintaining a fixation against the benefits of acquiring information from other regions of the scene (Tatler et al., 2017). As the benefits of maintaining fixation rise, so too does fixation duration. In situations defined by high perceptual or cognitive load, more thorough visual processing may be necessary and, as such, the benefits of maintaining fixation would increase. In the context of MW, as thoughts turn inward and attention decouples from external stimuli, visual processing may become less efficient and the visual system may more slowly encode and evaluate information at each fixated location. The benefits of maintaining fixation, therefore, may hold for longer periods of time, thus, increasing fixation duration. Indeed, past research has suggested that visual and cognitive processing difficulty can delay or even cancel saccade initiation, thereby resulting in prolonged fixation durations (Nuthmann et al., 2010; Vergilino-Perez, Collins, & Doré-Mazars, 2004; Yang & McConkie, 2001). Future investigations and models of gaze control need to account for the more complex relationship between MW, fixations, and visual processing than has been previously hypothesized to obtain a more complete understanding of the moment-to-moment information-processing priorities of the visual system.

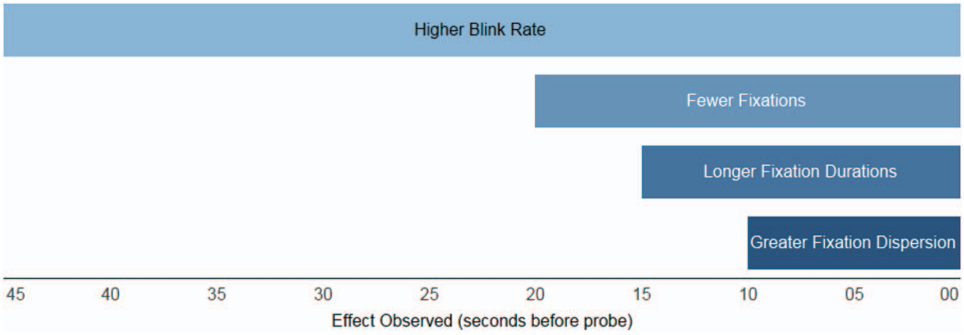

Figure 3. A summary of the gaze patterns associated with mind wandering (MW) and the time at which changes in patterns are observed. See the online article for the color version of this figure.

In addition to the temporal aspects of gaze, we also considered the relationship between MW and the spatial aspects of gaze (i.e., saccade amplitude and fixation dispersion), which are less constrained in scene viewing than in reading, and, hence, of great interest in the scene processing literature. Indeed, the current work suggests that fixation point selection during scene viewing is associated with MW. Not only did observers make fewer fixations during periods of MW, the dispersion of their fixations tended to increase. This suggests that the decrease in gaze samples was not randomly distributed throughout the scenes, but instead reflected a shift in sampling strategy. However, whether this shift reflects a global, context-free bias or a change in the degree to which content-dependent factors (e.g., visual salience, semantic content, etc.) affect gaze cannot be discerned from the present study. In fact, our results contrast with some work indicating that MW is associated with a narrowing in the dispersion of gaze within the context of driving (He, Becic, Lee, & McCarley, 2011). In driving simulators, before self-caught reports of MW, drivers have been shown to reduce their propensity to horizontally scan the environment, suggesting that MW can entail a failure to more broadly scan or monitor the visual world. This contrast suggests that while MW similarly affects the temporal dimensions of gaze across contexts, changes in the spatial allocation of gaze may vary across tasks.

Finally, we found that in the main experiment MW was associated with an increase in blink rate, a result that is also consistent with one study investigating MW during reading (i.e., Smilek et al., 2010). Eyeblinks are known to physically block and cognitively suppress incoming information (Gawne & Martin, 2000; Irwin, 2014; Thomas & Irwin, 2006; Volkmann, 1986; Volkmann et al., 1980) and are implicitly timed to minimize the probability of missing critical information (Nakano et al., 2009). Thus, our main experiment suggests that the implicit timing of blinks can systematically shift during MW, reducing the rate at which visual information is extracted. That said, a statistically significant effect of MW on blink rate was not found in the replication study. In fact, other reading-based studies have also not observed significant increases in blink rate associated with MW (Faber et al., 2017; Uzzaman & Joordens, 2011). Hence, the inconsistency within our own research mirrors inconsistencies apparent in the literature. Considered collectively, although the pattern of results suggests an increase in blink rate during MW, the finding should be considered tentative because of replication failures.

In addition to the theoretical implications of our work, identifying aspects of gaze control that are unique to MW in the context of scene viewing has several potential practical applications. For example, our results suggest that it may be possible to use gaze behaviors to detect MW in real-time within a variety of real-world contexts. Such detection could enable automated interventions that reorient attention to ongoing tasks (D'Mello, Mills, Bixler, & Bosch, 2017). To explore which of these gaze behaviors account for unique variance in MW, and how their combinations could be used to best detect MW, we conducted an exploratory linear mixed-effect logistic regression analysis in which we attempted to predict responses to the MW probes from gaze features collected in the main study. This model focused on the 10 s period preceding the thought probe, as it was within this window that fixation number, fixation duration, fixation dispersion, and blink rate were all associated with MW (see Figure 3). The model failed to converge when the number and duration of fixations were both included, likely because of the fact that they were strongly correlated (see Table 2). To compensate, we restricted our fixed-effect factors to the observed number of fixations, fixation dispersion, and number of blinks (scene viewing time was included as a fixed-effect covariate). We found that the number of fixations, $F(1, 743) = 22.6$, $p < .001$, $B = -.120$, followed by the number of blinks, $F(1, 743) = 4.74$, $p = .030$, $B = .175$, were the most robust predictors of MW. Fixation dispersion marginally predicted MW, $F(1, 743) = 2.56$, $p = .110$, $B = 1.27$. To more fully explore the marginal contribution of fixation dispersion, we computed a second model that excluded number of fixations (as it was correlated with fixation dispersion). In this case, fixation dispersion was a significant predictor of MW, $F(1, 744) = 12.1$, $p < .001$, $B = 2.52$. Collectively, these findings suggest that, when multiple gaze behaviors are considered in concert, the frequency of fixations and blinks account for unique variance in MW, although there is some evidence to suggest that fixation dispersion may nevertheless be a useful measure in this regard. These findings can serve as an important springboard for future research exploring the potential uses of real-time gaze-based detection of MW in applied contexts.

In conclusion, gaze allocation provides a real-time index of information-processing priorities of the visual system. The current research established global gaze-based indicators of MW during scene processing that reveal a reprioritization of the visual system similar (in some ways) to what has been found during reading, suggesting a common mechanistic shift unique to MW. These findings pose a challenge, however, for our current understanding of gaze control as computational models of gaze do not account for off-task attentional states, such as MW. Lastly, these findings provide estimation for when gaze-based indices of MW can be

Table 2
Pearson Correlation Coefficient Matrix for Gaze Behaviors and Mind Wandering Across 10 s Window

Gaze behaviors	Fixation durations	Saccade amplitude	Fixation dispersion	Number of blinks	Mind wandering
Number of fixations	−.784	.073	−.262	.114	−.235
Fixation duration	—	−.157	.195	−.412	.179
Saccade amplitude		—	−.020	.163	.051
Fixation dispersion			—	−.052	.093
Number of blinks				—	.055

Note. Not all time windows contained a fixation for each participant; thus, sample size varied slightly between variables.

reliably detected, which can be used to develop objective measures of MW during scene viewing.

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Appendix

Coefficients for All Variables in the Regression Models for the Main Experiment

	B	*SE*
Number of fixations		
Intercept	13.8	.523
Probe response: MW	−1.43	.352
Time window: 45–40 s	1.08	.252
Time window: 40–35 s	1.10	.253
Time window: 35–30 s	.818	.253
Time window: 30–25 s	.731	.252
Time window: 25–20 s	.786	.253
Time window: 20–15 s	.708	.253
Time window: 15–10 s	.517	.253
Time window: 10–5 s	.478	.252
Image2	.244	.266
Image3	−.671	.278
Image4	−.906	.274
Image5	−.249	.257
Image6	.283	.271
Image7	−.180	.284
Image8	−.417	.269
Image9	−.595	.267
Image10	−.511	.263
Image11	−.281	.258
Image12	.412	.285
ViewTime	−.023	.007
MW * Time window 45–40 s	1.24	.491
MW * Time window 40–35 s	1.05	.490
MW * Time window 35–30 s	1.04	.491
MW * Time window 30–25 s	.793	.490
MW * Time window 25–20 s	.402	.488
MW * Time window 20–15 s	.289	.489
MW * Time window 15–10 s	−.072	.489
MW * Time window 10–5 s	−.128	.488
Fixation duration		
Intercept	352	64.7
Probe response: MW	198	45.6
Time window: 45–40 s	−43.8	32.7
Time window: 40–35 s	−21.4	32.7
Time window: 35–30 s	−33.5	32.7
Time window: 30–25 s	−24.4	32.7
Time window: 25–20 s	−3.56	32.7
Time window: 20–15 s	−8.97	32.7
Time window: 15–10 s	−21.3	32.7
Time window: 10–5 s	−12.6	32.7
Image2	24.6	34.4
Image3	31.3	36.0
Image4	46.8	35.5
Image5	91.0	33.2
Image6	4.85	35.1
Image7	−4.14	36.7
Image8	31.5	34.8

(*Appendix continues*)

Appendix (*continued*)

	B	*SE*
Image9	55.0	34.5
Image10	36.1	34.0
Image11	54.0	33.4
Image12	34.2	36.9
ViewTime	.084	.856
MW * Time window 45–40 s	−172	63.3
MW * Time window 40–35 s	−202	63.3
MW * Time window 35–30 s	−164	63.3
MW * Time window 30–25 s	−175	63.2
MW * Time window 25–20 s	−87.2	63.5
MW * Time window 20–15 s	−120	63.6
MW * Time window 15–10 s	−50.0	63.5
MW * Time window 10–5 s	−60.7	63.6
Saccade amplitude		
Intercept	2.82	.189
Probe response: MW	−.076	.124
Time window: 45–40 s	−.007	.089
Time window: 40–35 s	−.032	.089
Time window: 35–30 s	.024	.089
Time window: 30–25 s	−.049	.089
Time window: 25–20 s	−.100	.089
Time window: 20–15 s	−.099	.089
Time window: 15–10 s	−.177	.089
Time window: 10–5 s	−.150	.089
Image2	−.034	.094
Image3	−.155	.098
Image4	−.203	.097
Image5	−.038	.090
Image6	.069	.095
Image7	−.281	.100
Image8	−.235	.095
Image9	−.088	.094
Image10	−.031	.093
Image11	−.077	.091
Image12	−.181	.100
ViewTime	.002	.002
MW * Time window 45–40 s	.093	.172
MW * Time window 40–35 s	.186	.172
MW * Time window 35–30 s	−.048	.172
MW * Time window 30–25 s	−.103	.172
MW * Time window 25–20 s	.146	.173
MW * Time window 20–15 s	.162	.173
MW * Time window 15–10 s	.420	.173
MW * Time window 10–5 s	.223	.173
Fixation dispersion		
Intercept	.216	.018
Probe response: MW	.025	.014
Time window: 45–40 s	−.010	.010
Time window: 40–35 s	−.006	.010
Time window: 35–30 s	.009	.010
Time window: 30–25 s	−.012	.010
Time window: 25–20 s	−.009	.010
Time window: 20–15 s	.005	.010
Time window: 15–10 s	.001	.010
Time window: 10–5 s	−.011	.010
Image2	.008	.010
Image3	−.010	.011
Image4	.014	.010
Image5	.023	.010

(*Appendix continues*)

Appendix (*continued*)

	B	*SE*
Image6	−.000	.010
Image7	−.006	.011
Image8	.014	.010
Image9	.001	.010
Image10	.015	.010
Image11	.009	.010
Image12	−.003	.011
ViewTime	.000	.000
MW * Time window 45–40 s	−.020	.019
MW * Time window 40–35 s	−.033	.019
MW * Time window 35–30 s	−.044	.019
MW * Time window 30–25 s	−.020	.019
MW * Time window 25–20 s	.005	.019
MW * Time window 20–15 s	−.025	.019
MW * Time window 15–10 s	−.009	.019
MW * Time window 10–5 s	.012	.019
Number of blinks		
Intercept	1.37	.229
Probe response: MW	.151	.134
Time window: 45–40 s	−.259	.096
Time window: 40–35 s	−.221	.096
Time window: 35–30 s	−.108	.096
Time window: 30–25 s	−.029	.096
Time window: 25–20 s	−.106	.096
Time window: 20–15 s	−.059	.096
Time window: 15–10 s	−.046	.096
Time window: 10–5 s	−.072	.096
Image2	.089	.102
Image3	.141	.106
Image4	.220	.105
Image5	.146	.098
Image6	.160	.104
Image7	.034	.108
Image8	−.034	.103
Image9	.011	.101
Image10	.088	.100
Image11	.250	.098
Image12	.109	.109
ViewTime	.007	.003
MW * Time window 45–40 s	.103	.186
MW * Time window 40–35 s	.111	.186
MW * Time window 35–30 s	.006	.186
MW * Time window 30–25 s	−.128	.186
MW * Time window 25–20 s	.151	.187
MW * Time window 20–15 s	.015	.187
MW * Time window 15–10 s	−.121	.187
MW * Time window 10–5 s	−.075	.187

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