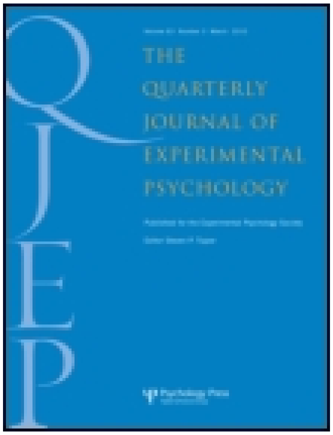

The Quarterly Journal of Experimental Psychology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/pqje20

Window to the wandering mind: Pupillometry of spontaneous thought while reading

Michael S. Franklin[a], James M. Broadway[a], Michael D. Mrazek[a], Jonathan Smallwood[b] & Jonathan W. Schooler[a]

[a] Department of Psychological and Brain Sciences, University of California, Santa Barbara, CA, USA

[b] Department of Psychology, University of York, York, UK

Accepted author version posted online: 23 Oct 2013.Published online: 09 Dec 2013.

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 2013
Vol. 66, No. 12, 2289–2294, http://dx.doi.org/10.1080/17470218.2013.858170

Rapid communication

Window to the wandering mind: Pupillometry of spontaneous thought while reading

Michael S. Franklin[1], James M. Broadway[1], Michael D. Mrazek[1], Jonathan Smallwood[2], and Jonathan W. Schooler[1]

[1]Department of Psychological and Brain Sciences, University of California, Santa Barbara, CA, USA
[2]Department of Psychology, University of York, York, UK

Mind-wandering is both pervasive and detrimental to task performance. As such, identifying covert physiological measures that are associated with this off-task state could inform theories of mind-wandering and lead to interventions that improve task focus. Although previous work suggests that pupil dilation (PD) may vary between on- and off-task states, no studies have examined whether PD systematically varies within a subject as they report becoming disengaged from a task—a key step in developing useful mind-wandering prediction algorithms. In the present study, PD was measured while participants advanced through a passage one word at a time. Spontaneous mind-wandering was assessed during reading using standard thought probe methodology. Results revealed higher PD prior to off-task than prior to on-task reading. This newly discovered relationship between momentary fluctuations of attention and PD offers promise for future innovations that use these systematic changes in PD to predict and better control mind-wandering.

Keywords: Mind-wandering; Pupil dilation; Attention.

It is well established that mind-wandering, or having one's attention diverted internally, away from the current task, is both pervasive and associated with a number of negative consequences. These negative consequences of mind-wandering have been demonstrated across different task contexts (for reviews see Mooneyham & Schooler, 2013; Smallwood & Andrews-Hanna, 2013) such as those requiring sustained attention (e.g., the sustained attention to response task, SART, Smallwood, McSpadden, & Schooler, 2008), during reading (Franklin, Smallwood, & Schooler, 2011; Schooler, Reichle, & Halpern, 2004; Smallwood et al., 2008), and learning and memory tasks (Mrazek et al., 2012; Smallwood, Obonsawin, & Heim, 2003). Mind-wandering also impacts mental health and is associated with negative mood, depression, and attention-deficit/hyperactivity disorder (ADHD; e.g., Carriere, Cheyne, & Smilek, 2008; Smallwood & O'Conner, 2011; Smallwood, O'Conner, Sudberry, & Oonsawin, 2007; Whalen, Jamner, Henker, Delfino, & Lozano). Therefore, developing ways to track attentional state in real time and know

Correspondence should be addressed to Michael S. Franklin, Department of Psychological and Brain Sciences, University of California, Santa Barbara, CA 93106, USA. E-mail: franklin@psych.ucsb.edu

Funding: M.S.F., M.D.M., J.M.B., J.S., and J.W.S. are supported through United States Department of Education [grant number R305A110277] awarded to J.S. and J.W.S.

The content of this article does not necessarily reflect the position or policy of the U. S. Government, and no official endorsement should be inferred.

when the mind has wandered could have important applications across many domains (e.g., cognitive, educational, industrial–organizational, and clinical). The present study focused on mind-wandering while reading, a common occurrence that has been shown to impair comprehension (Schooler et al., 2004; Smallwood et al., 2008).

Unfortunately, a major obstacle in identifying the correlates of mind-wandering is that knowing when a person is mind-wandering is inherently difficult, due to its spontaneity and reliance on self-reports for measurement (Smallwood & Schooler, 2006). Although experience sampling methodology has revealed that participants are able to accurately assess when their mind has wandered and has led to the discovery of various correlates of mind-wandering, uncovering covert measures of mind-wandering that do not rely on the frequent probing of participants may result in more effective interventions to reduce mind-wandering. Along these lines, Franklin et al. (2011) show that reaction times (RTs) while advancing text one word at a time vary based on mind-wandering and that it is possible to use this information to predict, in advance of a thought probe, whether a participant will say they are mind-wandering. Also, eye-tracking studies have shown that mind-wandering while reading is associated with longer fixations and reduced sensitivity to lexical features (Foulsham, Farley, & Kingstone, 2013; Reichle, Reineberg, & Schooler, 2010). However, since RT and fixation duration vary depending on the task and stimulus properties, this particular approach does not easily transfer across different task domains. In the current study, we investigated changes in baseline pupil dilation (PD), which can be measured noninvasively across a wide range of tasks, based on reports of on- versus off-task reading.

PD is associated with the locus coeruleus—norepinephrine (LC–NE) system, a major neurotransmitter system modulating general arousal and attention. Researchers have identified two basic modes of LC activity, tonic and phasic, which are associated with the modulation of baseline and event-related PD, respectively (Gilzenrat, Niewuwenhuis, Jepma, & Cohen, 2010). The association of greater cognitive effort with higher event-related PD has been extensively documented in the pupillometry literature (Kahneman, 1973; for a recent review see Laeng, Sirois, & Gredeback, 2012). Moreover, it has been recently discovered that event-related PD is inversely related to baseline PD, such that higher event-related PD is associated with lower baseline PD, and vice versa (Gilzenrat et al., 2010; Smallwood et al., 2011). Accordingly, while increased phasic LC activation and higher event-related PD are associated with greater cognitive effort, increased tonic LC activation and higher baseline PD are associated with task disengagement, drowsiness, and decreased task accuracy (Gilzenrat et al., 2010). Consistent with this pattern, in relation to mind-wandering, Smallwood et al. (2012) showed that retrospective reports of task-unrelated thoughts during a simple vigilance task were associated with higher baseline PD.

Such findings can be interpreted in the context of adaptive gain theory (Aston-Jones & Cohen, 2005) in which the LC–NE system uses information about the utility of a given task to affect how long an organism engages with it. When the perceived utility of a particular task is high, phasic-mode LC activation biases the organism to remain engaged with it (exploitation), a state that is associated with lower baseline PD and higher event-related PD. When the perceived utility is low, tonic-mode LC activation biases the organism to seek alternative tasks with which to engage (exploration), a state that is associated with higher baseline PD and lower event-related PD. Extending this account to the relationship between PD and mind-wandering, baseline PD would be higher when the utility of engaging with a given task is low relative to the utility of engaging with a different "task"—in the form of task-unrelated thoughts (Smallwood et al., 2012). In other words, higher baseline PD and lower event-related PD would be associated with a state of mind-wandering, whilst lower baseline PD and higher event-related PD would be associated with a state of task engagement.

Although previous findings suggest that high baseline PD is associated with mind-wandering, this prior work relied on retrospective measures of mind-wandering (Smallwood et al., 2012). Therefore, it remains unknown whether spontaneous fluctuations of attention away from the task, identified by the participant during the task, will result in accompanying changes in PD. This association would be necessary for the real-time prediction of mind-wandering within a single participant. Therefore, the major aim of this study was to assess whether there are within-participant variations in PD based upon mind-wandering.

In the present study, PD was measured as participants read a story, one word at a time, in order to better approximate earlier work with sustained attention tasks. Participants were occasionally interrupted by a thought probe that asked whether they were mind-wandering just prior to seeing the probe. This thought sampling methodology allows for the assessment of spontaneous mind wandering (Smallwood & Schooler, 2006). Based on previous work, we predicted that PD would be higher for off-task reading than for on-task reading.

Method

Participants and procedures

Twenty-eight undergraduates (8 male) participated in the study (mean age = 19.43 years, *SD* = 1.54). Participants received $10/hr in compensation. This study was conducted with the approval of the university's Institutional Review Board. Participants gave written informed consent.

Eye tracking

PD was measured using a Tobii 120 eye tracker (Tobii, Stockholm, Sweden) with a sampling rate of 125 Hz. Calibrations were done prior to data collection for each individual. Participants were seated on average 55.7 cm (*SD* = 99.2) from the eye tracker and did not use a chin rest or other immobilization device. The acquisition and preprocessing of the PD data followed the procedures of Smallwood et al. (2011, 2012). Specifically, any missing data points due to blinks, off-screen fixations, and/or eye-tracker malfunction were interpolated using basic linear interpolation, in which these gaps were filled with data forming a straight line between the two gap points. Data were median filtered (order 5) in order to remove spikes by replacing each point with the median of neighbouring points, low-pass filtered (10 Hz) and *z*-transformed. Participants were discarded if their resulting PD time series consisted of more than 50% interpolated data. The proportion of participants excluded due to poor data (22.2%) is consistent with that in other investigations (Murphy, Robertson, Balsters, & O'connell, 2011; Smallwood et al., 2011, 2012).

Since the words were on the screen for a brief and variable duration, with no fixation in between, phasic PD from individual words were unable to be discriminated. Therefore, in the present study we were unable to assess phasic PD effects (which would also be the case with more naturalistic reading paradigms). In all subsequent analyses and interpretation, PD is treated as a measure of tonic PD.

Materials

Text. The text used in this experiment was a shortened version of *The Red-Headed League* (Conan-Doyle, 2001[1892]), which was edited to approximately 5000 words. Twenty-three questions were designed for this text to assess comprehension. Each question had four possible answers. These same materials have been used in other mind-wandering and reading studies (Franklin et al., 2011; Smallwood et al., 2008).

Procedure

After a brief set of instructions, participants began the reading task. The text was presented word by word, centrally, in black on a white screen. Participants could advance the text by pressing the spacebar. Participants were asked to minimize blinking and movements while the words were appearing on the screen.

Twenty-six thought probes were presented to the participants at pseudorandom intervals that varied for each subject (ranging from 100–230 words). At these probes, participants were asked to consider whether, just prior to being probed, they were mind-wandering (by pressing "y" or "n").

Results

In order to investigate the effects of mind-wandering, we used a time window that extended 40 words (corresponding to approximately 10 seconds) prior to the thought probe (consistent with earlier work by Christoff, Gordon, Smallwood, Smith, & Schooler, 2009); on-task periods (when participants responded with an "n" to the thought probe) were compared to off-task periods (when participants responded with a "y"). Seven participants were not included in the on- versus off-task analysis because they reported always being on-task; therefore, the analyses investigating differences in on- versus off-task reading behaviour included 21 participants. Proportion off-task was 34.2% ($SD = 28.94$).

RT

A one-way repeated measures analysis of variance (ANOVA) revealed no difference in reaction times for on-task (mean RT = 251.02 ms, $SD =$ 105.97) versus off-task (mean RT = 241.70 ms, $SD = 89.06$), $F(1, 20) = 0.28$, $p = .60$.

Comprehension

Overall, participants performed above chance (25%) on the comprehension questions (mean accuracy = 53.50%, $SD = 0.13$). Comprehension accuracy correlated significantly with the proportion of participants' off-task probe reports ($r = -.37$, $p = .02$) indicating that participants that mind-wander tend to answer fewer comprehension questions correctly. A comparison of participants who mind-wander the most (top quartile) versus those who mind-wander the least (bottom quartile) reveals a significant difference in comprehension accuracy (low mind-wander = 57.5%; high mind-wander = 35.0%; $t(9) = 4.27$, $p = .003$); this further highlights the effects of mind-wander on performance.

Pupillometry

Figure 1 displays PD based on mind-wandering. This analysis included 13 participants whose PD data passed the quality control measures and who also had reported both on- and off-task episodes.[1] A one-way repeated measures ANOVA revealed a significant difference in PD, $F(1, 12) = 6.45$, $p = .03$; overall, participants had higher PD when off-task than when on-task. We also examined whether there was a relationship between overall pupil size (using the non-z-scored mean) and comprehension accuracy. Although positive ($r = .39$), this correlation was not significant ($p = .18$).

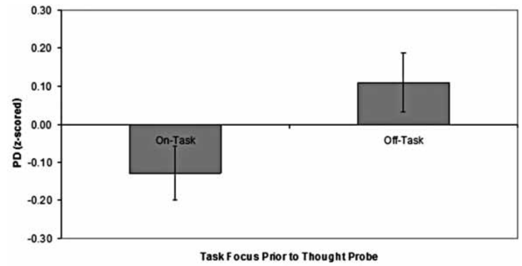

Figure 1. *Displays pupil dilation (PD) based on mind-wandering. Error bars representing 95% confidence intervals are plotted for this figure using methods taken from Loftus and Masson (1994).*

Discussion

The present results reveal for the first time that PD can be used to track attentional state within participants as they read. In particular, the results reveal that higher PD is associated with mindless (vs. mindful) reading when it occurs in a spontaneous manner. These results build upon recent work showing that high PD is associated with retrospective reports of mind-wandering and behavioural markers of inattention (Gilzenrat et al., 2010; Smallwood et al., 2012) and with earlier work positing a relationship between PD, the LC–NE system, and task engagement (Gilzenrat et al., 2010; Jepma & Nieuwenhuis, 2010). Moreover, noting the inverse relationship between baseline PD and event-related PD (Gilzenrat et al., 2010), these results are fully consistent with the long-standing association of greater cognitive effort

[1]The mean comprehension accuracy for these participants was 53.5%, the mean proportion MW was 31.06%, and the correlation between accuracy and MW was −.51 ($p < .01$).

with higher event-related PD (Kahneman, 1973; Laeng et al., 2012).

Finding covert measures of mind-wandering is an important step in developing techniques that could potentially disrupt ensuing mind-wandering episodes. The success of mindfulness training studies reveals that it is possible to reduce mind-wandering and improve task performance through a cognitive intervention (e.g., Mrazek et al., 2013). Future work will be needed to test whether it is similarly possible to improve attention and performance using feedback based on PD. Therefore, identifying PD as a covert marker of mindless reading, which is easily and unobtrusively measured (and even currently being developed for smartphones), holds promise for significant advances in both understanding and correcting the known costs of mind-wandering while reading (Schooler et al., 2004). Future studies will be needed to examine the relationship between PD and mind-wandering while reading under more naturalistic conditions along with the effectiveness of combining PD and measures of gaze duration to better predict mind-wandering. In addition, the correspondence between the present findings and earlier work showing a similar effect in a different task context (e.g., sustained attention tasks) suggests that PD could be used as an index of attention across a number of performance domains.

Through identifying PD as an indirect marker of mind-wandering that varies for participants as their attention shifts on and off task, the present results inform theories of mind wandering and also bring us one important step closer to knowing in real time when participants are mindlessly reading without having to ask them. This offers the possibility for interventions that not only improve reading comprehension but also benefit task performance across different domains. More generally, the present findings further illustrate the remarkable capacity of pupillometry to enable inferences about mental processes (Laeng et al., 2012). The eyes may or may not be a window to the soul, but they certainly can tell us a great deal about what is going on in the mind.

Original manuscript received 17 July 2013
Accepted revision received 30 September 2013
First published online 9 December 2013

REFERENCES

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience*, *28*, 403–450. doi:10.1146/annurev.neuro.28.061604.135709

Carriere, J. S. A., Cheyne, J. A., & Smilek, D. (2008). Everyday attention lapses and memory failures: The affective consequences of mindlessness. *Consciousness and Cognition*, *17*(3), 835–847. doi:10.1016/j.concog.2007.04.008

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*, *106*, 8719–8724. doi:10.1073/pnas.0900234106

Conan-Doyle, A. (2001). The red-headed league. In E. Glinert (Ed.),*The adventures and memoirs of Sherlock Holmes*. London: Penguin. (Original work published 1892).

Foulsham, T., Farley, J., & Kingstone, A. (2013). Mind wandering in sentence reading: Decoupling the link between mind and eye. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *67*(1), 51–59. doi:10.1037/a0030217

Franklin, M., Smallwood, J., & Schooler, J. (2011). Catching the mind in flight: Using behavioral indices to detect mindless reading in real time. *Psychonomic Bulletin & Review*, *18*(5), 992–997. doi:10.3758/s13423-011-0109-6

Gilzenrat, M. S., Nieuwenhuis, S., Jepma, M., & Cohen, J. D. (2010). Pupil diameter tracks changes in control state predicted by the adaptive gain theory of locus coeruleus function. *Cognitive, Affective, & Behavioral Neuroscience*, *10*(2), 252–269. doi:10.3758/CABN.10.2.252

Jepma, M., & Nieuwenhuis, S. (2010). Pupil diameter predicts changes in the exploration–Exploitation trade-off: Evidence for the adaptive gain theory. *Journal of Cognitive Neuroscience*, *23*(7), 1587–1596. doi:10.1162/jocn.2010.21548

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice-Hall.

Laeng, B., Sirois, S., & Gredebäck, G. (2012). Pupillometry: A window to the preconscious? *Perspectives on Psychological Science*, *7*(1), 18–27. doi:10.1177/1745691611427305

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review*, *1*(4), 476–490. doi:10.3758/BF03210951

Mooneyham, B. W., & Schooler, J. W. (2013). The costs and benefits of mind-wandering: A review. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *67*(1), 11–18. doi:10.1037/a0031569

Mrazek, M. D., Franklin, M. S., Phillips, D. T., Baird, B., & Schooler, J. W. (2013). Mindfulness training improves working memory capacity and GRE performance while reducing mind wandering. *Psychological Science*, *24*(5), 776–781. doi:10.1177/0956797612459659

Mrazek, M. D., Smallwood, J., Franklin, M. S., Chin, J. M., Baird, B., & Schooler, J. W. (2012). The role of mind-wandering in measurements of general aptitude. *Journal of Experimental Psychology, 141*(4), 788–798. *General*. doi:10.1037/a0027968

Murphy, P. R., Robertson, I. H., Balsters, J. H., & O'connell, R. G. (2011). Pupillometry and P3 index the locus coeruleus–Noradrenergic arousal function in humans. *Psychophysiology*, *48*(11), 1532–1543. doi:10.1111/j.1469-8986.2011.01226.x

Reichle, E. D., Reineberg, A. E., & Schooler, J. W. (2010). Eye movements during mindless reading. *Psychological Science*, *21*(9), 1300–1310. doi:10.1177/0956797610378686

Schooler, J. W., Reichle, E. D., & Halpern, D. V. (2004). Zoning out while reading: Evidence for dissociations between experience and metaconsciousness. In D. T. Levin (Ed.), *Thinking and seeing: Visual metacognition in adults and children* (pp. 203–226). Cambridge, MA: MIT Press.

Smallwood, J., & Andrews-Hanna, J. (2013). Not all minds that wander are lost: The importance of a balanced perspective on the mind-wandering state. *Frontiers in Psychology*, *4*, 441. doi:10.3389/fpsyg.2013.00441

Smallwood, J., Brown, K. S., Baird, B., Mrazek, M. D., Franklin, M. S., & Schooler, J. W. (2012). Insulation for daydreams: A role for tonic norepinephrine in the facilitation of internally guided thought. *PloS One*, *7*(4), e33706. doi:10.1371/journal.pone.0033706

Smallwood, J., Brown, K. S., Tipper, C., Giesbrecht, B., Franklin, M. S., Mrazek, M. D., … Schooler, J. W. (2011). Pupillometric evidence for the decoupling of attention from perceptual input during offline thought. *PLoS ONE*, *6*(3), e18298. doi:10.1371/journal.pone.0018298

Smallwood, J., McSpadden, M., & Schooler, J. (2008). When attention matters: The curious incident of the wandering mind. *Memory & Cognition*, *36*(6), 1144–1150. doi:10.3758/MC.36.6.1144

Smallwood, J., Obonsawin, M., & Heim, D. (2003). Task unrelated thought: The role of distributed processing. *Consciousness and Cognition, 12*(2), 169–189. doi:10.1016/S1053-8100(02)00003-X

Smallwood, J., & O'Connor, R. C. (2011). Imprisoned by the past: Unhappy moods lead to a retrospective bias to mind wandering. *Cognition & Emotion*, *25*(8), 1481–1490. doi:10.1080/02699931.2010.545263

Smallwood, J., O'Connor, R. C., Sudbery, M. V., & Obonsawin, M. (2007). Mind-wandering and dysphoria. *Cognition & Emotion*, *21*(4), 816–842. doi:10.1080/02699930600911531

Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin*, *132*(6), 946–958. doi:10.1037/0033-2909.132.6.946

Whalen, C. K., Jamner, L. D., Henker, B., Delfino, R. J., & Lozano, J. M. (2002). The ADHD spectrum and everyday life: Experience sampling of adolescent moods, activities, smoking, and drinking. *Child Development*, *73*(1), 209–227. doi:10.1111/1467-8624.00401