Drowsiness or mind-wandering? Fluctuations in ocular parameters during attentional lapses

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Abstract

Two independent lines of evidence suggest that drowsiness and mind-wandering share common neurocognitive processes indexed by ocular parameters (e.g., eyeblink frequency and pupil dynamics). Mind-wandering and drowsiness frequently co-occur, however, such that it remains unclear whether observed oculometric variations are related to mind-wandering, drowsiness, or a mix of both. To address this issue, we assessed fluctuations in mind-wandering and sleepiness during a sustained attention task while ocular parameters were recorded. Results showed that oculometric variations during mind-wandering were fully explained by increased sleepiness. However, mind-wandering and sleepiness had additive deleterious effects on performance that were not fully explained by ocular parameters. These findings suggest that oculometric variations during task performance reflect increased drowsiness rather than processes specifically involved in mind-wandering, and that the neurocognitive processes indexed by oculometric parameters (e.g., regulatory processes of the locus coeruleus norepinephrine system) do not fully explain how mind-wandering and sleepiness cause attentional lapses.

Keywords: mind-wandering; pupillometry; eyeblinks; drowsiness; attentional lapses.

1. Introduction

Everyday activities such as driving or attending a lecture require to maintain attentional focus on relevant information over extended periods of time (Engle & Kane, 2004). Failures in sustaining attention often result in attentional lapses (Broadbent, Cooper, FitzGerald, & Parkes, 1982; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), which can have negative and sometimes dramatic consequences (e.g., driving or railway accidents; Edkins & Pollock, 1997; Reason, 1984; Warm, 1984). Attentional lapses are frequently linked to the occurrence of task-unrelated thoughts, either in the form of external distractions or mind-wandering episodes (Stawarczyk, Majerus, Maj, Van der Linden, & D'Argembeau, 2011; Unsworth, Brewer, & Spillers, 2012; Unsworth, McMillan, Brewer, & Spillers, 2012). External distractions occur when attention is temporally grasped by sensory experiences that are unrelated to the task at hand (e.g., being distracted while driving because of a smartphone vibrating or because of a sudden urge to sneeze), whereas mind-wandering episodes correspond to a switch of attentional focus from the current task to internally generated thoughts that are decoupled from the here and now, such as memories of past events, personal concerns, or plans about the future (Lustig, Hasher, & Tonev, 2001; Smallwood & Schooler, 2015; Stawarczyk et al., 2011; Unsworth & McMillan, 2014).

Task-unrelated thoughts have been investigated in laboratory tasks and daily life activities by means of a thought-probe method that consists in randomly presenting probes that ask people to report whether they were fully focused on task or whether they were thinking about something else just before being asked (Robison, Miller, & Unsworth, 2019; Smallwood & Schooler, 2006; Weinstein, 2018). Studies using this method suggest that mind-wandering and external distractions represent from 30 to 50% of our daily thinking time (Kane et al., 2007; Killingsworth & Gilbert, 2010). Although task-unrelated thoughts can have beneficial effects (e.g., the detection of threats in the external environment or the elaboration of future plans; Baird, Smallwood, & Schooler, 2011; Medea et al., 2018; Stawarczyk, 2018; Stawarczyk, Cassol, & D’Argembeau, 2013), the shift of attention focus away from the task at hand is often associated with decreased task performance (Mooneyham & Schooler, 2013; Randall, Oswald, & Beier, 2014). For instance, during the Sustained Attention to Response Tasks (SART; Robertson et al., 1997; Smilek, Carriere, & Cheyne, 2010a), one of the most commonly used task to assess attentional lapses, mind-wandering and external distractions have been consistently associated with lower accuracy and more variable response times (RTs; McVay & Kane, 2009, 2012; Stawarczyk & D’Argembeau, 2016; Stawarczyk, Majerus, Catale, & D’Argembeau, 2014; Stawarczyk et al., 2011). Furthermore, studies using ecological assessments in naturalistic situations have found that task-unrelated thoughts are associated with hazardous driving practices (Baldwin et al., 2017; He, Becic, Lee, & McCarley, 2011; Lemercier et al., 2014; Pepin et al., 2018; Qu et al., 2015; Yanko & Spalek, 2014), including road crash responsibility (Galera et al., 2012; Gil-Jardiné et al., 2017), and with decreased memory for information presented during lectures, which may lead to poor academic performance (Farley, Risko, & Kingstone, 2013; Lindquist & McLean, 2011; Mrazek, Franklin, Phillips, Baird, & Schooler, 2013; Wammes, Seli, Cheyne, Boucher, & Smilek, 2016).

Mind-wandering and external distractions are not the only causes of attentional lapses, with ample evidence showing that sleep-related disturbances also negatively impact attention during the day. Daytime sleepiness corresponds to the tendency to doze off or fall asleep during daily activities, mostly because of a lack of sleep due to inadequate sleep and waking times (Hershner & Chervin, 2014; Lund, Reider, Whiting, & Prichard, 2010). Recent epidemiological studies suggest that this phenomenon is particularly frequent in young adults, with sleep disturbances affecting from 15 to 25% of college students (Buboltz et al., 2009; Ford, Cunningham, Giles, &

Croft, 2015; Taylor, Bramoweth, Grieser, Tatum, & Roane, 2013). Daytime sleepiness and related sleep disturbances have been associated with attentional lapses of similar nature as those induced by task-unrelated thoughts, notably impaired RTs and accuracy during laboratory attention tasks, including the SART (Gobin, Banks, Fins, & Tartar, 2015; Jackson & Van Dongen, 2011; Larue, Rakotonirainy, & Pettitt, 2010; Lim & Dinges, 2008; Short & Banks, 2014), an increased risk of driving accidents (Connor et al., 2002; Garbarino, Nobili, Beelke, De Carli, & Ferrillo, 2001; MacLean, Davies, & Thiele, 2003), and poorer academic performance (Curcio, Ferrara, & De Gennaro, 2006; Gaultney, 2010; Gomes, Tavares, & de Azevedo, 2011).

Interestingly, an increasing body of evidence suggests that task-unrelated thoughts and daytime sleepiness are closely linked. For instance, studies using sleep deprivation procedures have found that a lack of sleep is associated with more frequent reports of task-unrelated thoughts during attentional tasks (Mikulincer, Babkoff, Caspy, & Weiss, 1990; Poh, Chong, & Chee, 2016; Schwarz et al., 2017). In addition, several studies have reported a positive correlation between mind-wandering and shorter sleep duration or sleep disturbances, as assessed by self-rated questionnaires (Baker, Baldwin, & Garner, 2015; Carciofo, Du, Song, & Zhang, 2014; Ottaviani & Couyoumdjian, 2013; Shaw et al., 2010; Walker & Trick, 2018). Finally, research using thought-probes in daily life have found that individuals report being off-task more frequently when they are more tired (Kane et al., 2007, 2017; McVay, Kane, & Kwapil, 2009). Together, these studies suggest that daytime sleepiness and task-unrelated thoughts frequently co-occur, although the exact nature of the association between these two phenomena remains unclear.

The relations between off-task thinking, daytime sleepiness, and attentional lapses were formally assessed in a recent study by Stawarczyk and D'Argembeau (2016). Fluctuations in daytime sleepiness during the SART were assessed using the Karolinska Sleepiness Scale (KSS, a 9-point Likert scale assessing the extent to which individuals are alert and awake; Akerstedt & Gillberg, 1990) at each thought-probe, along with the assessment of mind-wandering and external distractions (for studies reporting the validity of this procedure to assess daytime sleepiness, see Kaida, Akerstedt, Kecklund, Nilsson, & Axelsson, 2007; Kaida et al., 2006; Schleicher, Galley, Briest, & Galley, 2008). As expected, Stawarczyk and D'Argembeau (2016) found that self-reported sleepiness gradually increased with time on task. Furthermore, individual differences in mind-wandering during the task were correlated with sleepiness. Interestingly, sleepiness and mind-wandering were independent predictors of task performance (i.e., both uniquely contributed to attentional lapses). Similar results were found at the within-participant level: task-unrelated thoughts (mind-wandering and external distractions) and sleepiness provided independent contribution to the prediction of attentional lapses. These results suggest that although task-unrelated thoughts and daytime sleepiness tend to co-occur, they are at least partly distinct phenomena that have additive deleterious effects on task performance.

A question that remains is whether task-unrelated thoughts and daytime sleepiness have distinct physiological correlates. Similar fluctuations in ocular parameters have indeed been reported in studies of mind-wandering and in studies of daytime sleepiness. Studies investigating eyelid movements during task performance have found that task-unrelated thoughts are associated with more frequent (Frank, Nara, Zavagnin, Touron, & Kane, 2015; Grandchamp, Braboszcz, & Delorme, 2014; Krasich et al., 2018; Smilek, Carriere, & Cheyne, 2010b) and longer (Grandchamp et al., 2014; Huette, Mathis, & Graesser, 2016) eyeblinks compared to moments when individuals are fully focused on task. In parallel to these findings, eyeblink frequency and duration are well-known indicators of daytime sleepiness and fatigue (e.g., Caffier, Erdmann, & Ullsperger, 2003; He et al., 2017; Körber, Cingel, Zimmermann, & Bengler, 2015; Schleicher et al., 2008).

Somewhat surprisingly, however, the increased blink rate and duration observed during task-unrelated thoughts have not been discussed in relation to drowsiness. Instead, changes in these ocular parameters have been attributed to perceptual decoupling: the higher blink rate and longer blink duration during mind-wandering would reflect an isolation process from visual inputs that facilitates the generation and maintenance of internal mentation (Huette et al., 2016; Salvi & Bowden, 2016; Smilek et al., 2010b). This proposal is supported by findings of increased blink rates and blink duration, as well as attenuated processing of external stimuli, during tasks requiring the generation and manipulation of information that is decoupled from sensory inputs (e.g., creative idea generation; Annerer-Walcher, Körner, & Benedek, 2018; Benedek, Stoiser, Walcher, & Körner, 2017; Salvi, Bricolo, Franconeri, Kounios, & Beeman, 2015; Walcher, Körner, & Benedek, 2017). However, the extent to which the increased frequency and duration of blinks during mind-wandering reflects perceptual decoupling or drowsiness remains unclear.

Besides eyeblinks, increasing evidence suggests that pupil diameter may also be an indicator of attentional lapses (Hopstaken, van der Linden, Bakker, & Kompier, 2015b, 2015a; Unsworth & Robison, 2016; Unsworth, Robison, & Miller, 2018; van den Brink, Murphy, & Nieuwenhuis, 2016). During task requiring sustained attention to external stimuli, mind-wandering episodes have been associated with reduced and variable pupil diameters at both the within- and between-individual levels (Faber, Bixler, & D'Mello, 2018; Grandchamp et al., 2014; Konishi, Brown, Battaglini, & Smallwood, 2017; Mittner et al., 2014; Unsworth & Robison, 2017, 2018; but see Franklin, Broadway, Mrazek, Smallwood, & Schooler, 2013). To the difference of eyelid parameters, these fluctuations in pupil size have been interpreted as a potential marker of fatigue and sleepiness. The reduction in pupil size during task-unrelated thoughts might reflect a tonic hypoactivation of the locus coeruleus norepinephrine system, which is involved in the regulation of alertness and arousal, and higher variations in pupil size would reflect difficulties in maintaining a stable level of alertness and arousal over time, thus causing attentional lapses (for a recent review, see Unsworth & Robison, 2017).

The locus coeruleus is a small nucleus of the brain-stem that is the source of norepinephrine for the cerebral cortex and its activity is closely associated with arousal and circadian rhythm (Berridge & Waterhouse, 2003; Jouvet, 1969; Samuels & Szabadi, 2008; Szabadi, 2013). Neural activity within the locus coeruleus positively correlates with pupil size (e.g., Joshi, Li, Kalwani, & Gold, 2016; Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014) and it has been shown that optimal task performance is associated with an intermediate activity level of this nucleus, with hypoactivation leading to attentional lapses caused by low alertness and arousal, and hyperactivation leading to task disengagement caused by anxiety and distractibility (Aston-Jones & Cohen, 2005; Cohen, Aston-Jones, & Gilzenrat, 2004). Given the close relation between arousal and daytime sleepiness (Bakotić & Radošević-Vidaček, 2012), it is likely that the reduced and variable pupil diameters that are observed during mind-wandering correspond to increased fatigue and sleepiness. However, to date, no study has assessed pupil parameters in relation to task-unrelated thoughts and daytime sleepiness within the same experimental paradigm. Pupil size being determined by a multitude of physiological and cognitive factors besides arousal and locus coeruleus activity (for recent reviews, see Larsen & Waters, 2018; Mathot, 2018), it is possible that variables other than sleepiness and alertness are associated with changes in pupil diameter during mind-wandering. For instance, studies that compared ocular parameters during tasks requiring attention to either external stimuli or internal thoughts have found larger pupil diameters for internally directed attention, possibly caused by a higher cognitive workload or attentional effort compared to tasks involving external attention (e.g., Benedek et al., 2017; van der Wel &

van Steenbergen, 2018; Walcher et al., 2017). It could thus be that, after controlling for sleepiness, mind-wandering would be associated with increased pupil sizes, reflecting the cognitive demands required to generate and maintain internal thoughts while shielding them from interfering sensory inputs (Smallwood, 2013). This may explain why a minority of studies have found larger rather than smaller pupil sizes in association with mind-wandering (Franklin et al., 2013; for more indirect evidence, see also Smallwood et al., 2012, 2011).

In summary, various ocular parameters (blink frequency, blink duration, mean pupil diameter, and variability of pupil diameter) have been related to task-unrelated thoughts and daytime sleepiness. However, no study to date has attempted to jointly assess these two sources of attentional lapses, such that it remains unclear whether mind-wandering and sleepiness have distinguishable ocular correlates. This is particularly important because there is currently a surge in research using ocular parameters in attempts to develop automated systems that monitor the occurrence of task-unrelated thoughts (e.g., Faber et al., 2018; Gwizdka, 2019; Mittner et al., 2014; Zhao, Lofi, & Hauff, 2017) or drowsiness (e.g., François, Hoyoux, Langohr, Wertz, & Verly, 2016; He et al., 2017; Jackson et al., 2016; Rost et al., 2015). However, the ability of these systems to distinguish between drowsiness and task-unrelated thoughts remains unclear. Determining whether some variations in ocular parameters are more sensitive to the occurrence of mind-wandering or daytime sleepiness would help further develop these novel detection methods. Furthermore, specifying the ocular correlates of mind-wandering and sleepiness might also help to determine the extent to which their effects on task performance have similar physiological bases.

To address these questions, we asked a group of participants to perform a version of the SART with probes assessing both sleepiness and task-unrelated thoughts, while changes in blink and pupil parameters were recorded using photo-oculography (François et al., 2016). Besides replicating the additive effect of task-unrelated thoughts and daytime sleepiness on task performance (Stawarczyk & D'Argembeau, 2016), our aim was to investigate to what extent fluctuations in ocular parameters during the SART are related to task-unrelated thoughts, sleepiness, or a combination of both. On the one hand, if fluctuations in some ocular parameters during mind-wandering reflect cognitive processes that are specific to this mental state (e.g., perceptual decoupling), then these parameters (i.e., longer and more frequent eyeblinks, and increased pupil diameter) should be associated with mind-wandering even when sleepiness is taken into account. On the other hand, if the changes in ocular parameters that are observed during mind-wandering result from increased drowsiness, then mind-wandering should no longer be associated with measures of eyeblinks and pupil size when sleepiness is taken into account. Finally, another aim of the present study was then to assess whether the deleterious effects of sleepiness and mind-wandering on task performance depend on neurocognitive processes indexed by ocular parameters (e.g., dysregulations of the locus coeruleus norepinephrine system). If this is the case, the effects of mind-wandering and sleepiness on SART performance should be accounted for by fluctuations in pupil diameter and blink features.

2. Methods

The fully anonymized data files and coded data, as well as all the study materials can be obtained from the first author upon request. This study was approved by the Ethics Committee of the Department of Psychology, Speech Therapy, and Education of the University of Liège. Informed consent was obtained from all the participants before the beginning of the study and the methods were carried out in accordance with the relevant guidelines and regulations. We report all measures, manipulations, and data exclusions below, as well as how we determined sample size (Simmons, Nelson, & Simonsohn, 2011).

2.1. Participants

Thirty-three participants (25 women) took part in this study (mean age = 21.76 years, *SD* = 2.02, range = 18 – 25 years). All of them were students at the University of Liège, with a mean of 2.70 completed years of higher education (*SD* = 1.65, range = 0-6 years). One additional participant was tested but excluded from the final sample because ocular parameters could not be reliably extracted from the data. Individuals with delayed sleep schedules (e.g., shift workers) or suffering from medical, neurological, or psychiatric disorders were not included in the study. A power analysis computed in R using the SIMR package (Green & MacLeod, 2016) on the data from our previous experiment using a similar experimental task (Stawarczyk & D'Argembeau, 2016) revealed that this sample size was sufficient to replicate the within-subject additive effects of thought-probe responses and KSS scores on attentional lapses during the SART (as indexed by accuracy to the target stimuli) with a power of 99.7% (95% CI [99.13, 99.94] and alpha value of .05. The mean subjective sleep duration reported by our participants in the 7 days preceding the testing session was 7.57 hr (*SD* = 1.17, range = 5 – 11 hr). This duration is similar to the usual sleep length reported by college students in western countries (Lund et al., 2010) and to the values reported in our previous study with a sample drawn from a similar population (Stawarczyk & D'Argembeau, 2016). Participants received a monetary compensation of 15 euros for their participation.

2.2. SART with embedded thought-probes and KSS.

Participants carried out an adaptation of the SART used in Stawarczyk & D'Argembeau (2016). Numbers comprised between 1 and 9 were sequentially presented in the center of a laptop computer screen and participants were instructed to respond as fast and accurately as possible to each number (i.e., the non-target stimuli) by pressing the spacebar on the keyboard, except when presented with the number 3 (i.e., the target stimulus; 11% of probability of appearance) for which they were told to withhold their response. Each stimulus was presented in white font (Arial with a point size of 72) on a black background for 500 ms, with an interstimulus interval of 2,000 ms (Smallwood et al., 2004). The task consisted in 30 blocks of either 30, 45, 60, 75 or 90 s. The blocks were randomly presented with the limitation that each set of 5 blocks comprised one block of each length. The last five stimuli of each block were always non-targets and at least one trial per block was a target stimulus. The blocks were immediately followed by the KSS (Akerstedt & Gillberg, 1990), which interrupted the task and asked participants how they felt right before the interruption. The KSS is a measure of subjective sleepiness that consists in a 9-point Likert scale ranging from 1 (completely alert) to 9 (very sleepy, great effort to keep awake).

Immediately after the KSS, participants were asked to characterize the ongoing conscious experience they had just prior the interruption (Stawarczyk et al., 2011). Five possibilities were provided: (a) *on-task*: the participant's attention and thoughts were fully focused on the task-related stimuli; (b) *task-related interference*: the participant experienced thoughts about some task features or about their performance (e.g., thoughts about task duration or about the participant's overall performance; participants were explained that this category comprised all thoughts about the task that did not help them to respond as fast and accurately as possible to the numbers presented on the screen); (c) *external distraction*: the participant's attention was focused on stimuli that were present in the current environment but unrelated to the task at hand (e.g., exteroceptive perceptions or interoceptive sensations; it was explained that this category comprised all thoughts whose content was directly focused on current sensory perceptions unrelated to the task at hand, with the origin of these perceptions being either the surrounding environment or bodily sensations); (d) *mind-wandering*: the participant had his or her attention decoupled from the current environment and was experiencing thoughts unrelated to the task at hand (e.g., thoughts about what the participant will do later in the day[1]); and (e) *absence*: the participant's attention was not focused on the task at hand and he or she was not thinking about anything in particular, meaning that his or her mind was blank (Ward & Wegner, 2013). After each thought probe, a short text was displayed on the screen asking participants to press the spacebar to continue the task. As in our previous studies (Stawarczyk & D'Argembeau, 2016; Stawarczyk et al., 2014, 2011), several examples reflecting each category of experience were provided to the participants and they were asked to classify 10 thoughts in the adequate category before the beginning of the SART. They also carried out two training blocks before starting the complete task.

Three indices of task performance were extracted from the data. The first index was the accuracy of responses to the target stimuli for each block of the task, which is commonly used as a measure of attentional lapses during the SART. In addition, we also extracted the coefficient of variation (CV) of RTs and the mean RT to the non-target stimuli for each block, as several studies have shown that a higher variability of RTs and more impulsive RTs reflect an inadequate (mindless) processing of the task stimuli (e.g., Cheyne, Solman, Carriere, & Smilek, 2009; McVay & Kane, 2012; Robertson et al., 1997; Smilek et al., 2010a; Stawarczyk et al., 2011).

2.3. Ocular parameters

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[1] As in our previous studies, it was explained to the participants that their answers should only be based on the content of their thoughts, irrespective of their possible triggers. For instance, if a participant was thinking of their upcoming birthday because the number 4 presented during the task reminded them that it will happen on the fourth of next month, they were instructed to categorize this thought as mind-wandering. Similarly, if a participant was thinking about what kind of sandwich to get after the experiment because they were starting to feel hungry during the task, this would count as mind-wandering. In short, participants were instructed to classify such thoughts as instances of mind-wandering regardless of whether these thoughts were triggered by the task or the current environment.

Ocular parameters were recorded using photo-oculography: participants wore a drowsiness monitoring system (prototype of Drowsimeter R100, from Phasya; François et al., 2016) that consists in a pair of eyeglasses that includes a high-speed camera, an infrared illumination source, and a hot mirror. The system provides the values of several ocular parameters extracted from images of the eye that are linked to the movement of the eyelids (including blinks) and pupil size. Specifically, we used image processing algorithms to precisely extract the positions of both eyelids and the position of the pupil in each image of the eye. We then computed several ocular parameters over a time window that corresponded to the duration of each block of the SART. The positions of the eyelids enabled us to measure the opening of the eye. As the average opening of the eye varies greatly from one individual to another, we computed a baseline for each individual in order to obtain a normalized measure of eye opening. We next computed ocular parameters related to blinks and closures of the eye from this normalized measure. The values for blink frequency and blink duration were extracted for each of the 30 blocks of SART. Finally, we determined the pupil diameter from the position of the pupil in each image using another set of algorithms and then extracted the values for mean pupil diameter and standard deviation of the pupil diameter over the duration of each of the 30 blocks of SART.

2.4. Procedure

After completing the informed consent form, participants filled a demographic questionnaire and a series of self-report questionnaires assessing their sleep pattern and attention failures in daily life (details on these questionnaires are reported in the supplementary materials but will not be examined here any further as our sample size was not large enough for individual difference analyses). They were then given the instructions of the SART and carried out the two training blocks. While the instructions were being given, electrodes were placed on the participants' head and torso for EEG and ECG recordings (these data are not reported here as they are not relevant to the hypotheses tested in the present paper). Participants then performed the SART with thought probes while wearing the drowsiness monitoring system. After completing the task, they were informed that the experiment was over and were asked to fill a monetary compensation form while the EEG and ECG electrodes were removed. The total duration of the testing session was approximately 75 min and an experimenter stayed in the testing room with the participant for the whole duration of the experiment.

3. *Results*

The data were analyzed using mixed-effects models with participants as random effects. All the models were fitted using the robustlmm package in R (Koller, 2016) and mind-wandering was used as the reference category in all analyses including the category of experience as predictor. This allowed us not only to compare how ocular parameters differed between mind-wandering and on-task reports but also between mind-wandering and external distractions. Because data were aggregated across blocks of different durations, block length was included in all models as a fixed effect covariate of no interest. The models including KSS scores, thought-probe responses, SART performance, and blink parameters were performed on the 990 blocks of the task nested within the 33 participants. Analyses on pupil parameters were performed on 846 blocks nested within 29 participants as these ocular parameters could not be reliably extracted from all blocks and participants. The effects package (Fox, 2003) was used to estimate the fixed effects for plotting. Finally, the within-correlation matrix between the different ocular parameters was computed in R using the statsBy function of the psych package (Revelle, 2018).

3.1. Variations of sleepiness with time on task and thought-probe responses

To investigate whether sleepiness increased with time on task, we performed a growth curve analysis to assess changes in KSS scores over the 30 thought-probes with second-order orthogonal polynomials (i.e., linear and quadratic terms; Mirman; 2014). As shown in **Figure 1a**, KSS scores increased with time on task and results showed that both the linear ($b = 5.93$, $SE = 0.20$, $t = 29.41$, $p < .001$) and quadratic term ($b = -0.85$, $SE = 0.20$, $t = -4.20$, $p < .001$) were significant, indicating that the slope modeling the increase in sleepiness during the task was steeper at the beginning than end of the SART. The average increase in sleepiness during the entire task (slightly more than 3 points on the scale) is similar to previous observations (Bonnefond, Doignon-Camus, Touzalin-Chretien, & Dufour, 2010; Stawarczyk & D'Argembeau, 2016).

Regarding thought-probe responses, out of the 990 probes, 297 (30%) were on-task reports, 293 (29.60%) were task-related interferences, 191 (19.29%) were external distractions, 165 (16.67%) were mind-wandering episodes, and 44 (4.44%) were absence reports. A mixed-effects model was used to examine whether sleepiness (KSS scores) varied as a function of responses to the thought-probes. As shown in **Figure 1b**, results showed that on-task reports ($b = -1.63$, $SE = 0.16$, $t = -9.98$, $p < .001$), task-related interferences ($b = -0.82$, $SE = 0.16$, $t = -5.25$, $p < .001$), and external distractions ($b = -0.39$, $SE = 0.17$, $t = -2.24$, $p = .03$) were associated with lower KSS scores than mind-wandering, whereas no significant difference was found between mind-wandering and absence reports ($b = 0.48$, $SE = 0.28$, $t = 1.74$, $p = .08$).

3.2. SART performance as a function of sleepiness and thought-probe responses

We examined whether SART performance varied as a function of responses to the thought-probes and then added KSS scores to the models to determine whether we could replicate the additive effect of task-unrelated thoughts and sleepiness on task performance. Regarding accuracy to the target stimuli, results showed that on-task reports were associated with higher accuracy than mind-wandering (*b* = 16.36, *SE* = 3.38, *t* = 4.84, *p* < .001); mind-wandering did not differ from task-related interferences (*b* = 1.60, *SE* = 3.27, *t* = 0.49, *p* = .62), external distractions (*b* = -0.13, *SE* = 3.59, *t* = -0.04, *p* = .97), and absence reports (*b* = -7.11, *SE* = 5.77, *t* = -1.23, *p* = .22; see **Figure 2a**). The difference in target accuracy between mind-wandering and on-task reports remained significant when adding KSS scores to the model (*b* = 9.23, *SE* = 3.46, *t* = 2.67, *p* = .008), and KSS scores were associated with lower target accuracy (*b* = -4.34, *SE* = 0.66, *t* = -6.63, *p* < .001). All the other effects remained non-significant (all *p*'s ≥ .43; see **Figure 2a**).

A similar pattern of results was found for the CV of RTs to the non-target stimuli, with on-task reports being associated with lower RT variability than mind-wandering (*b* = -2.45, *SE* = 0.58, *t* = -4.22, *p* < .001), while no difference was observed between mind-wandering and task-related interferences (*b* = -0.57, *SE* = 0.56, *t* = -1.01, *p* = .31), external distractions (*b* = -0.12, *SE* = 0.62, *t* = -0.19, *p* = .85), and absence reports (*b* = 1.05, *SE* = 0.99, *t* = 1.06, *p* = .29; see **Figure 2b**). When adding KSS scores to the model, the difference in RT variability between mind-wandering and on-task reports remained significant (*b* = -1.91, *SE* = 0.61, *t* = -3.13, *p* = .002; see **Figure 2b**), and higher KSS scores were associated with more variable RTs (*b* = 0.35, *SE* = 0.12, *t* = 2.96, *p* = .003). All the other effects remained non-significant (all *p*'s ≥ .37).

Finally, with regard to the mean RT to the non-target stimuli, results revealed that mind-wandering was associated with faster (i.e., more impulsive or mindless) RTs than on-task reports (*b* = 9.14, *SE* = 2.72, *t* = 3.36, *p* < .001) and task-related interferences (*b* = 8.51, *SE* = 2.61, *t* = 3.26, *p* = .001), but did not differ from external distractions (*b* = 5.11, *SE* = 2.89, *t* = 1.78, *p* = .08) and absences reports (*b* = 0.75, *SE* = 4.62, *t* = 0.16, *p* = .87; see **Figure 2c**). Adding the KSS scores to the model did not change the significance of the results regarding on-task reports (*b* = 6.11, *SE* = 2.84, *t* = 2.15, *p* = .03) and task-related interferences (*b* = 6.96, *SE* = 2.62, *t* = 2.65, *p* =

.008), and higher KSS scores were associated with more impulsive RTs to the non-target stimuli (*b* = -2.12, *SE* = 0.56, *t* = -3.83, *p* < .001). Again, all the other effects remained non-significant (all *p*'s ≥ .13; see **Figure 2c**). Together, these results replicate our previous findings showing that, although sleepiness and mind-wandering are related, they have additive deleterious effects on SART performance (Stawarczyk & D'Argembeau, 2016).

3.3. Ocular parameters as a function of sleepiness and thought-probe responses

3.3.1. Pupil diameter

Our next aim was to investigate whether the differences in pupil diameter that have been associated with mind-wandering reports in previous studies can be explained by variations in arousal, as proposed by the locus coeruleus norepinephrine account (Unsworth & Robison, 2017). If arousal level fully explains the variations in pupil diameter associated with mind-wandering, then the differences in mean and standard deviation of pupil diameter between the thought-probe responses should not remain significant once KSS scores are taken into account.

Regarding mean pupil diameter, results showed that mind-wandering was associated with smaller pupil sizes than on-task reports (*b* = 1.34, *SE* = 0.27, *t* = 5.00, *p* < .001), task-related interferences (*b* = 0.74, *SE* = 0.26, *t* = 2.84, *p* = .005), and external distractions (*b* = 0.64, *SE* = 0.28, *t* = 2.26, *p* = .02); there was no difference between mind-wandering and absence reports (*b* = -0.21, *SE* = 0.44, *t* = -0.48, *p* = .63; see **Figure 3a**). However, the differences between mind-wandering and on-task reports (*b* = 0.34, *SE* = 0.26, *t* = 1.26, *p* = .20), task-related interferences (*b* = 0.20, *SE* = 0.25, *t* = 0.81, *p* = .42), and external distractions (*b* = 0.23, *SE* = 0.26, *t* = 0.86, *p* = .39) were no longer significant when entering KSS scores in the model; the difference with absence reports remained non-significant (*b* = -0.04, *SE* = 0.41, *t* = -0.11, *p* = .91; see **Figure 3a**). Higher KSS scores were associated with smaller pupil sizes (*b* = -0.56, *SE* = 0.05, *t* = -11.46, *p* < .001).

Regarding the standard deviation of the pupil diameter, results revealed that mind-wandering was associated with a more variable pupil size than on-task reports (*b* = -0.22, *SE* = 0.90, *t* = -2.40, *p* = .01), but did not differ from task-related interferences (*b* = -0.05, *SE* = 0.09, *t* = -0.55, *p* = .58), external distractions (*b* = -0.11, *SE* = 0.09, *t* = -1.20, *p* = .23), and absence reports (*b* = 0.15, *SE* = 0.15, *t* = 1.03, *p* = .30; see **Figure 3b**). After adding KSS scores to the model, the difference between mind-wandering and on-task reports was no longer significant (*b* = -0.09, *SE* = 0.09, *t* = -1.00, *p* = .32), while higher KSS scores were associated with more variable pupil size (*b* = 0.07, *SE* = 0.02, *t* = 4.04, *p* < .001). All the other effects remained non-significant (all *p*'s ≥ .36; see **Figure 3b**).

Together, these results indicate that the differences in pupil diameter associated with mind-wandering are fully explained by changes in daytime sleepiness, in line with the locus coeruleus norepinephrine account of fluctuations in pupil diameter during mind-wandering (Unsworth & Robison, 2017).

3.3.2. Blink parameters

If blinking is specifically involved in the perceptual decoupling aspect of mind-wandering (Huette et al., 2016; Salvi & Bowden, 2016; Smilek et al., 2010b), then blink frequency and duration should be larger during mind-wandering than when attention is focused on the external environment (i.e., on-task reports and external distractions). Furthermore, mind-wandering should be associated with larger blinking parameters even when sleepiness is taken into account.

Regarding blink frequency, results showed that mind-wandering was associated with more frequent eyeblinks than on-task reports (*b* = -0.04, *SE* = 0.01, *t* = -3.43, *p* < .001) and task-related interferences (*b* = -0.02, *SE* = 0.01, *t* = -2.04, *p* = .04). There was no difference between mind-wandering and external distractions (*b* = -0.01, *SE* = 0.01, *t* = -0.92, *p* = .36) or absence reports (*b*

= -0.01, *SE* = 0.02, *t* = -0.80, *p* = .42; see **Figure 4a**). The difference between mind-wandering and on-task reports (*b* = -0.02, *SE* = 0.01, *t* = -1.72, *p* = .09) and task-related interferences (*b* = -0.01, *SE* = 0.01, *t* = -1.07, *p* = .28) was no longer significant after adding KSS scores to the model, and higher KSS scores were related to more frequent blinks (*b* = 0.01, *SE* = 0.002, *t* = 4.68, *p* < .001). All the other effects remained non-significant (all *p*'s ≥ .30; see **Figure 4a**).

In terms of blink duration, results showed that mind-wandering was associated with longer blinks than on-task reports (*b* = -7.21, *SE* = 2.58, *t* = -2.80, *p* = .005) but no difference was found with the other thought-probe responses: task-related interferences (*b* = -4.05, *SE* = 2.47, *t* = -1.64, *p* = .10), external distractions (*b* = -2.58, *SE* = 2.71, *t* = -0.95, *p* = .34), and absences (*b* = 5.15, *SE* = 3.37, *t* = 1.18, *p* = .24; see **Figure 4b**). When adding KSS score to the model, the difference between mind-wandering and on-task reports became non-significant (*b* = -2.34, *SE* = 2.70, *t* = -0.87, *p* = .38), and higher KSS scores were associated with longer blinks (*b* = -3.34, *SE* = 0.53, *t* = 6.36, *p* < .001). All the other effects remained non-significant (all *p*'s ≥ .36; see **Figure 4b**).

Together, these results do not support the view that blinks during mind-wandering reflect perceptual decoupling (Huette et al., 2016; Salvi & Bowden, 2016; Smilek et al., 2010b). First, the frequency and duration of blinks did not differ between mind-wandering and external distractions. Second, the difference between mind-wandering and on-task reports were fully explained by the KSS scores, suggesting that changes in blink parameters associated with mind-wandering are due to increased sleepiness rather than perceptual decoupling *per se*.

3.4. Can the effects of mind-wandering and sleepiness on task performance be accounted for by the neurocognitive processes indexed by ocular parameters?

Finally, we sought to investigate whether the effects of mind-wandering and sleepiness on SART performance can be accounted for by variations in ocular parameters. To do so, we first performed mixed-effects analyses to determine whether the ocular parameters were associated with SART performance in the expected directions. As the four ocular parameters were only weakly correlated (see **Table S2**), we included all four measures together as predictors in the models[2], with indices of SART performance as dependent variable. We then computed models with the ocular parameters, KSS scores and thought probe-responses as fixed effects to examine whether the additive effect of mind-wandering and sleepiness on task performance remained significant.

For accuracy to the target stimuli, the analyses with the ocular parameters as fixed effects showed that higher blink frequency (b = -17.53, SE = 6.44, t = -2.72, p = .007) and longer blink duration (b = -0.09, SE = 0.03, t = -3.28, p = .001) were both associated with lower accuracy. No significant relationships were found for mean pupil diameter (b = 0.03, SE = 0.25, t = 0.12, p = .90) or the standard deviation of pupil diameter (b = 1.26, SE = 1.11, t = 0.91, p = .26). For the CV of RTs to the non-targets, higher blink frequency (b = 3.05, SE = 1.18, t = 2.59, p = .01), longer blink duration (b = 0.014, SE = 0.005, t = 2.79, p = .005), and a smaller pupil diameter (b = -0.14, SE = 0.05, t = 2.79, p = .005) were all associated with more variable RTs. No significant effect was found for the variability of pupil diameter (b = 0.19, SE = 0.20, t = 0.93, p = .35). Finally, for the mean RT to non-target stimuli, only blink duration (b = -0.06, SE = 0.03, t = -2.53, p = .01) was associated with shorter (i.e., impulsive or mindless) RTs; no significant effect was found for blink frequency (b = -7.14, SE = 5.91, t = -2.53, p = .23), mean pupil diameter (b = 0.23, SE =

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[2] To account for the proposal that both low and high pupil diameter might cause attentional lapses due to respectively hypo- and hyperactivation of the locus coeruleus norepinephrine system (Aston-Jones & Cohen, 2005; Berridge & Waterhouse, 2003), we also computed models with the addition of a quadratic term for mean pupil diameter. This quadratic term was not significant in any of the models and we thus only report here the simpler analyses where mean pupil diameter was modeled with a single linear regressor.

0.29, *t* = 0.82, *p* = .41), and standard deviation of the pupil diameter (*b* = 1.50, *SE* = 0.99, *t* = 1.51, *p* = .13).

Given that the ocular parameters were overall associated with task performance in the expected directions, we investigated whether these ocular parameters accounted for the effects of sleepiness and mind-wandering on SART performance. Regarding accuracy to the target stimuli, we found that the effects of mind-wandering and sleepiness remained significant when ocular parameters were taken into account. More specifically, on-task reports (*b* = 9.24, *SE* = 3.78, *t* = 2.44, *p* = .01) were still associated with higher accuracy than mind-wandering, and KSS scores were still associated with decreased accuracy (*b* = -4.17, *SE* = 0.70, *t* = -5.97, *p* < .001). In this model, higher blink frequency was also still associated with lower target accuracy (*b* = -13.31, *SE* = 6.28, *t* = -2.12, *p* = .03) and the standard deviation of the pupil diameter became significantly associated with accuracy (*b* = 2.22, *SE* = 1.08, *t* = 2.06, *p* = .04), suggesting that, after controlling for sleepiness and thought-probe responses, more variations in pupil diameter are associated with fewer attentional lapses. All other effects were non-significant (all *p*s ≥ .25). The effects of mind-wandering and sleepiness on the CV of RTs to the non-target stimuli also remained significant when ocular parameters were taken into account, with RTs being less variable for on-task reports than mind-wandering (*b* = -2.24, *SE* = 0.69, *t* = 3.26, *p* = .001) and more variable with higher KSS scores (*b* = 0.28, *SE* = 0.12, *t* = 2.22, *p* = .03). Blink frequency (*b* = 2.56, *SE* = 1.16, *t* = 2.21, *p* = .03) and pupil diameter (*b* = -0.10, *SE* = 0.05, *t* = 2.79, *p* = .047) also remained associated with task performance. All other effects were not significant (all *p*s ≥ .08). Finally, for the mean RT to non-target stimuli, the differences between mind-wandering and on-task reports (*b* = 4.60, *SE* = 3.27, *t* = 1.41, *p* = .16) and task-related interferences (*b* = 5.03, *SE* = 3.05, *t* = 1.65, *p* = .10) were no longer significant when ocular parameters were entered in the model. However, higher KSS scores remained associated with shorter (more impulsive) RTs (b = -2.14, SE = 0.63, t = 3.34, p < .001). All other effects were non-significant (all ps ≥ .07).

Together these results indicate that the deleterious effects of sleepiness and mind-wandering reports on task performance cannot be fully explained in terms of the neurocognitive processes indexed by fluctuations in pupil diameters and eyeblink features.

4. Discussion

Recent research suggests that several ocular parameters (pupil diameter, blink frequency, and blink duration) are sensitive to increased drowsiness and the occurrence of task-unrelated thoughts. However, it remains unclear whether these two sources of attentional lapses have distinguishable ocular correlates and affect task performance through similar neurocognitive processes. This issue is particularly important as two distinct streams of research using oculography are currently attempting to develop drowsiness and mind-wandering monitoring systems, with the aim of preventing attentional lapses in real life situations. So far, the extent to which these monitoring systems capture attentional fluctuations specifically caused by either drowsiness or task-unrelated thoughts is equivocal. To shed light on this issue, we used a version of the SART with probes that assessed both the occurrence of task-unrelated thoughts and sleepiness, while fluctuations in participants' pupil diameter and blink features were recorded.

In line with previous studies (e.g., Bonnefond et al., 2010; Schneider et al., 2008; Stawarczyk & D'Argembeau, 2016), we found that sleepiness gradually increased with time on task and that the occurrence of mind-wandering was related to sleepiness. Considering this relation between mind-wandering and sleepiness, our goal was then to examine whether these two sources of attentional lapses are associated with distinct ocular parameters. Our results showed that the four ocular parameters investigated here were associated with mind-wandering in the expected direction: blinks were longer and more frequent, and pupil diameter showed a reduced a more variable size in task blocks that were associated with mind-wandering than in blocks where participants reported being fully focused on the task (see also, Grandchamp et al., 2014; Huette et al., 2016; Smilek et al., 2010b; Unsworth & Robison, 2017). Most importantly, however, the inclusion of KSS scores in addition to thought-probe responses in the regression models indicated that sleepiness significantly predicted changes in all ocular parameters and that the differences between mind-wandering and on-task reports were no longer significant when sleepiness was taken into account. These results suggest that fluctuations in ocular parameters with task-unrelated thoughts mostly result from increased drowsiness rather than processes specifically associated with mind-wandering *per se*[3].

These findings have important implications for understanding the basis of fluctuations in ocular parameters that are observed during mind-wandering. Previous accounts have suggested that higher blink rates and duration during off-task thoughts reflect perceptual decoupling (i.e., an isolation process from sensory inputs that facilitates the generation and maintenance of internal thoughts; Huette et al., 2016; Salvi & Bowden, 2016; Schooler et al., 2011; Smilek et al., 2010b). The present results showing that the higher frequency and duration of eyeblinks during mind-wandering was fully accounted for by sleepiness do not support this proposal. Furthermore, according to the perceptual decoupling account, mind-wandering should be associated with more frequent and longer blinks than both on-task reports and external distractions, as these two types of experiences reflect an attentional focus on current sensory inputs (Stawarczyk et al., 2014, 2011;

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[3] Note that the relation between mind-wandering and ocular parameters might differ in situations that involve high levels of arousal. Indeed, preliminary evidence suggests that when arousal is excessive (e.g., following stress induction procedures), mind-wandering might be associated with increases in pupil size (Unsworth & Robison, 2018).

Unsworth & McMillan, 2014). However, we found that mind-wandering did not differ from external distractions in terms of blink features. Therefore, it seems that the longer and more frequent blinks that are observed during task-unrelated thoughts are physiological markers of difficulties to stay focused on task (lower arousal and alertness) rather than a perceptual decoupling process that facilitates the generation and maintenance of internal thoughts.

Increases in blink rates and duration with higher drowsiness may reflect a loosening of cognitive control processes that help maintain attentional focus on the task at hand while filtering out irrelevant information that is internally generated (i.e., mind-wandering) or perceived by sensory organs (i.e., external distractions; Lustig et al., 2001). In line with this view, there is evidence that more frequent eye blinks reflect (at least in part) a dysregulation of the dopaminergic system, whose receptors in the prefrontal cortex and striatum respectively support the active maintenance of task-relevant information and gating mechanisms that prevent interference from distracting stimuli (for reviews, see Cools & D'Esposito, 2011; Jongkees & Colzato, 2016; Robbins & Arnsten, 2009). Evidence in favor of this attention control account notably comes from studies showing that the occurrence of blinks corresponds to moments when attentional control is relaxed while watching video stories (e.g., at the end of an action or when the same scene is repeated; Nakano, Yamamoto, Kitajo, Takahashi, & Kitazawa, 2009) and increases when performing low demand tasks (e.g., Lean & Shan, 2012; Maffei & Angrilli, 2018). In addition, more frequent eye blinks have been related to increased distractibility by irrelevant stimuli in switching tasks (e.g., Dreisbach et al., 2005; Müller et al., 2007; Tharp & Pickering, 2011). The increased blink rate found in the present study in relation with sleepiness might thus result from a less efficient regulation of attentional control processes supported by the dopaminergic system in the striatum and prefrontal cortex. Although this proposal fits well with neuroimaging studies showing dopaminergic dysregulations in these brain areas during sleep deprivation (e.g., Krause et al., 2017; Volkow et al., 2009), it should be noted that eyeblinks are modulated by a large variety of factors, among which the most obvious is probably the need to rehydrate the eye surface (for a review, see Cruz, Garcia, Pinto, & Cechetti, 2011). Further studies should therefore be conducted to further assess this dopaminergic account, especially regarding the duration of blinks where evidence is much scarcer.

The view that fluctuations in ocular parameters associated with off-task thoughts reflect a decreased neuromodulation of attention control processes is also concordant with our findings regarding pupil diameter. Specifically, we found that mind-wandering was associated with smaller and more variable pupil diameters than on-task reports and that these differences in pupil size were fully accounted for by increased sleepiness. These results are consistent with the view that the small pupil diameters observed during mind-wandering episodes reflect an hypoactivation of the locus coeruleus norepinephrine system (resulting in attentional lapses due to low alertness and arousal), and that the higher variability of pupil diameter indicates difficulties in maintaining an optimal level of alertness during the task (Unsworth & Robison, 2017). At the neural level, smaller and more variable pupil diameters might reflect reduced mobilization of fronto-parietal cortical areas involved in attentional control and moment-to-moment task engagement (Spreng, Stevens, Chamberlain, Gilmore, & Schacter, 2010; Vincent, Kahn, Snyder, Raichle, & Buckner, 2008) by the locus coeruleus norepinephrine system. By evaluating variations in self-reported sleepiness during the task, our study provides the first direct evidence that pupil diameter fluctuations during mind-wandering are fully explained by increased drowsiness.

We also examined the effects of task-unrelated thoughts and daytime sleepiness on SART performance, as well as the physiological bases of these effects as indexed by ocular parameters.

The results first replicated the additive deleterious effects of mind-wandering and sleepiness on task performance (target accuracy as well as CV and mean of RTs to the non-target stimuli) observed in our previous study (Stawarczyk & D'Argembeau, 2016). Intriguingly, however, we found that these effects remained significant after variations in ocular parameters had been taken into account, with the exception of the faster (i.e., more impulsive or mindless) RTs associated with mind-wandering. These results suggest that the deleterious effects of mind-wandering and sleepiness on task performance rely (at least in part) on neurocognitive processes other than those indexed by the ocular parameters investigated here (i.e., dysregulation of the dopaminergic and norepinephrine systems; see above). Neuroimaging studies of sleep deprivation have indeed shown that increased sleep pressure affects a variety of brain functions that extend beyond those directly related to dopamine and norepinephrine systems (for reviews, see Goel, Basner, Rao, & Dinges, 2013; Goel, Rao, Durmer, & Dinges, 2009; Krause et al., 2017). Regarding mind-wandering, a recent computational neuroimaging study has revealed that brain activity and ocular parameters both uniquely contribute to classifier performance when attempting to predict thought-probe responses (Mittner et al., 2014). Combining neuroimaging with oculography might thus shed additional light on the psychophysiological processes by which mind-wandering and drowsiness cause attentional lapses. More generally, the present results suggest that including repeated subjective reports of sleepiness in experimental paradigms might prove particularly useful to more comprehensively assess the extent to which drowsiness affects performance over time (for a similar discussion, see Hopstaken et al., 2015b, 2015a).

Although our results do not support the view that eye blinks (and to a lesser extent variations in pupil size) reflect perceptual decoupling, it is important to note that they do not discredit the perceptual decoupling theory altogether (Smallwood, 2013). In particular, perceptual decoupling might explain why mind-wandering was related to attentional lapses even when the effects of sleepiness, pupil size, and eyeblink features were taken into account. Future studies should be conducted to determine whether some physiological measures can specifically index the occurrence of perceptual decoupling during mind-wandering. For instance, numerous EEG studies have shown that a variety of event-related potentials (ERP) associated with sensory processing (such as the early P1 and N1 components that originate from primary sensory areas or the P300 that index the depth of cognitive processing devoted to task-relevant stimuli) are disrupted during mind-wandering (for reviews, see Handy & Kam, 2015; Martinon, Smallwood, McGann, Hamilton, & Riby, 2019). It would be interesting to investigate whether disruptions in these ERP components are specifically related to mind-wandering or whether they can be accounted for by increased sleepiness, as it is the case for blink parameters and pupil size in this study.

In conclusion, the main finding of the present study is that fluctuations in blink duration, blink frequency, mean pupil diameter, and standard deviation of pupil diameter during task performance are better explained by difficulties in maintaining on-task focus due to increased drowsiness rather than processes specifically associated with mind-wandering. These results support the locus coeruleus norepinephrine account of mind-wandering and suggest that variations in blink parameters during mind-wandering are not due to perceptual decoupling processes but may instead reflect a dysregulation in the striato-prefrontal dopaminergic system supporting attentional control processes during task performance. However, the effects of mind-wandering and sleepiness on task performance were not fully accounted for by fluctuations in these ocular parameters, suggesting that the physiological processes linking mind-wandering and drowsiness to behavioral lapses extend beyond those investigated here. An important implication of these findings is that oculography studies aiming at developing mind-wandering monitoring systems (e.g., Faber et al., 2018; Gwizdka, 2019; Mittner et al., 2014; Zhao et al., 2017) might be currently more sensitive to the increased drowsiness that is concomitant to the occurrence of off-task thoughts rather than mind-wandering *per se*. Further studies should be conducted to determine if the occurrence of mind-wandering and sleepiness can be distinguished on the basis of other physiological markers.

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Figures

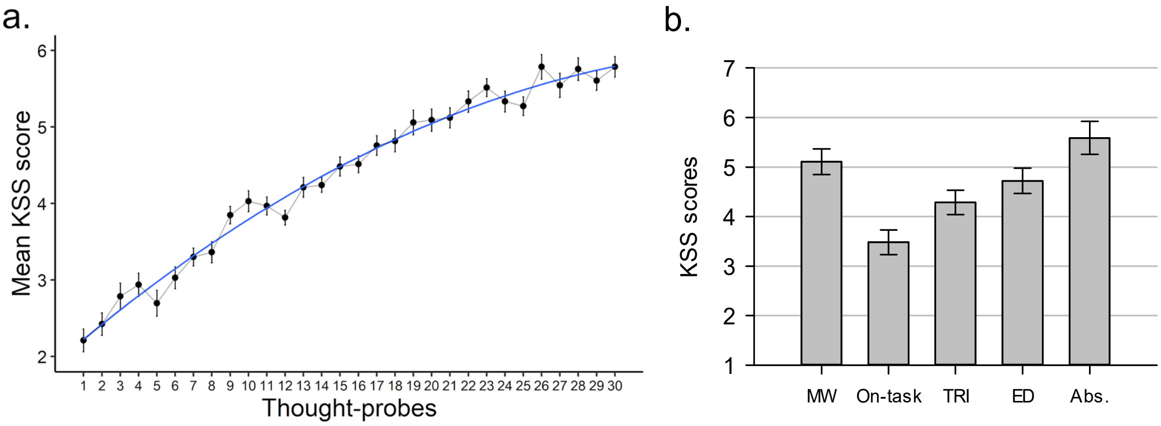

Figure 1. Panel a. illustrates the variation in the mean KSS scores with time on task and the fitted quadratic curve. Error bars represent the standard error of the mean. Panel b. illustrates the KSS scores and standard errors estimated from the linear mixed model with the thought-probe responses as fixed effect of interest. KSS = Karolinska Sleepiness Scale TRI = task-related interference; ED = external distraction; MW = mind-wandering; Abs. = absence.

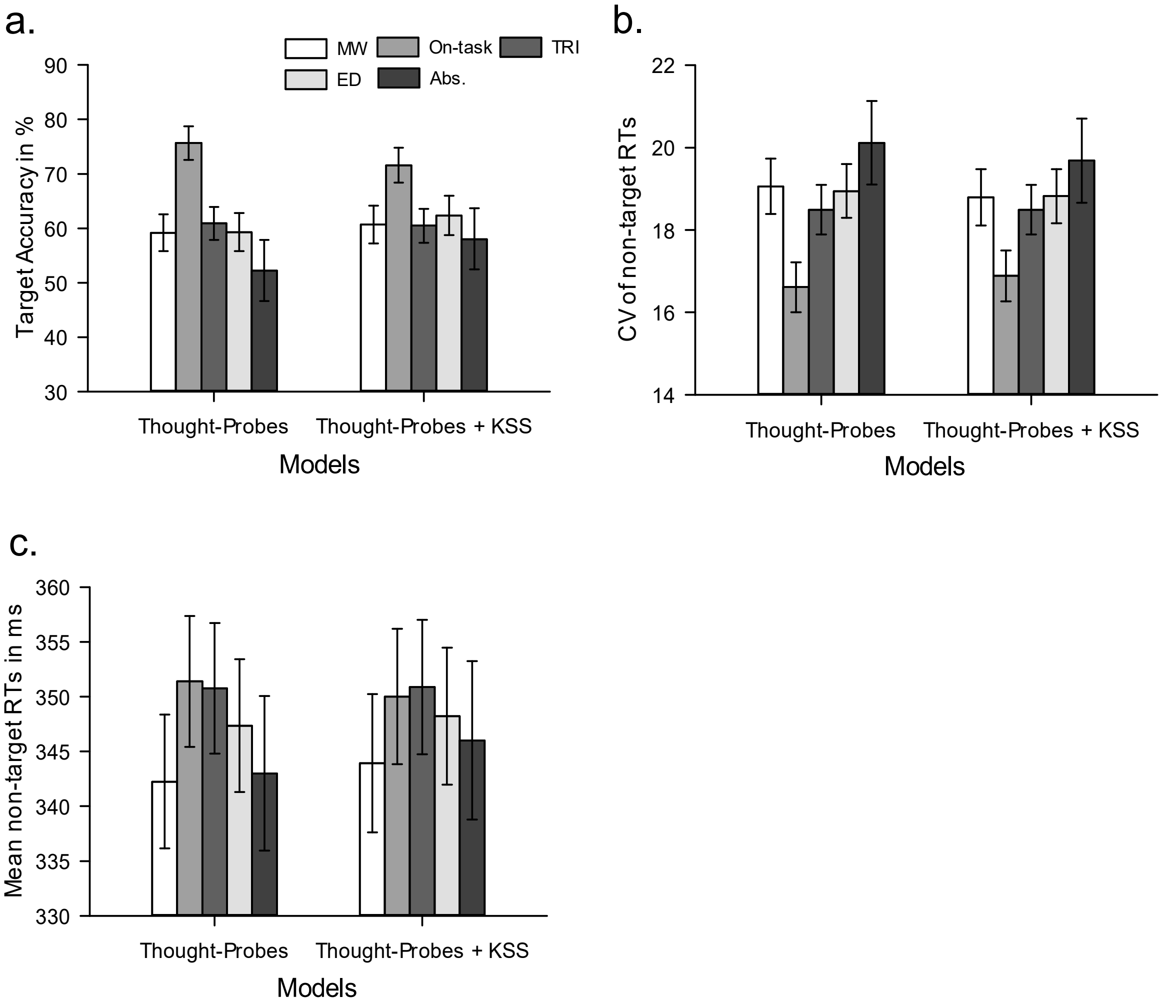

Figure 2. Differences in mean target accuracy (panel a), coefficient of variation of RTs to non-targets (panel b), and mean RTs to non-targets (panel c) as a function of thought-probe responses. The mean values and standard errors are estimated from the linear mixed models with thoughts-probe responses only (left) or with both thought-probe responses and KSS scores as fixed effects of interest (right). RT = response time; CV = coefficient of variation; KSS = Karolinska Sleepiness Scale TRI = task-related interference; ED = external distraction; MW = mind-wandering; Abs. = absence.

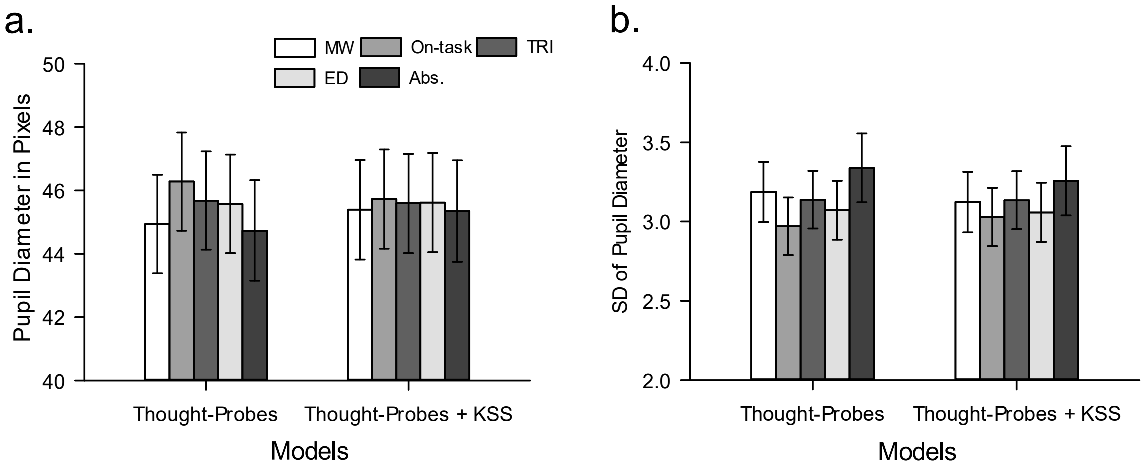

Figure 3. Differences in mean pupil diameter (panel a) and standard deviation of pupil diameter (panel b) as a function of thought-probe responses. The mean values and standard errors are estimated from the linear mixed models with thoughts-probe responses only (left) or with both thought-probe responses and KSS scores as fixed effects of interest (right). SD = standard deviation; KSS = Karolinska Sleepiness Scale TRI = task-related interference; ED = external distraction; MW = mind-wandering; Abs. = absence.

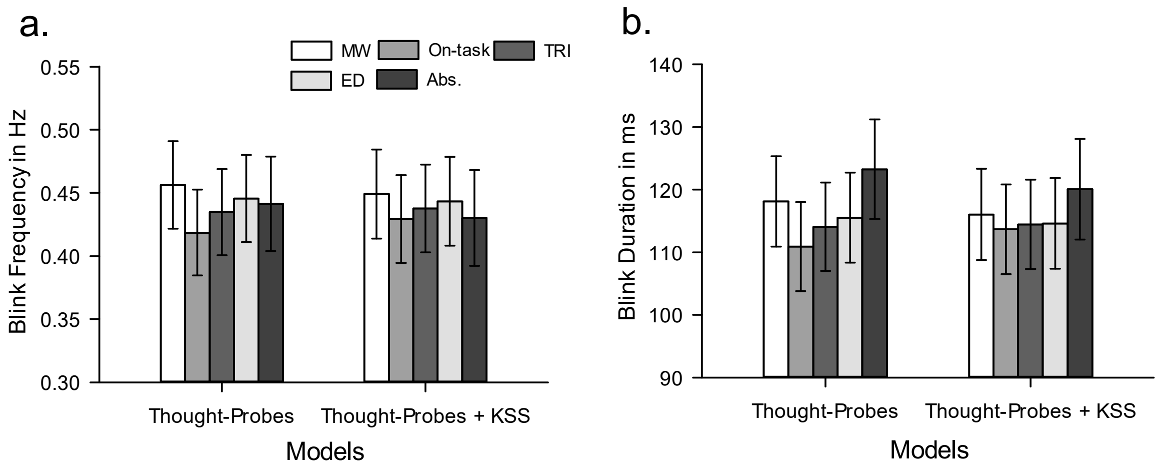

Figure 4. Differences in blink frequency (panel a) and blink duration (panel b) as a function of thought-probe responses. The mean values and standard errors are estimated from the linear mixed models with thoughts-probe responses only (left) or with both thought-probe responses and KSS scores as fixed effects of interest (right). KSS = Karolinska Sleepiness Scale TRI = task-related interference; ED = external distraction; MW = mind-wandering; Abs. = absence.