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Bore me (not): boredom impairs recognition memory but not the pupil old/new effect

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Bore me (not): boredom impairs recognition memory but not the pupil old/new effect

Abstract

Mind-wandering and boredom are common phenomena, characterized by shifts in attention and difficulties in sustaining focus. Despite extensive research on the costs and benefits of these states, our understanding of the relationship between mind-wandering, boredom, attention, and memory remains limited. In the current study, we examined the impact that mind-wandering and boredom during encoding have on recognition. In particular, we investigated what impact mind-wandering and boredom have during the encoding of visual stimuli on the pupil old/new effect during recognition. We used an incidental memory task and measured mind-wandering and boredom with thought probes during encoding. Furthermore, we used the pupil old/new effect, assessed via eye-tracking, as a measure of recognition memory. We found a significant effect of boredom on recognition memory and observed the pupil old/new effect in participants regardless of instances of mind-wandering or boredom during encoding. Our findings point towards different mechanisms that underly mind-wandering and boredom's obstruction of attention during stimuli encoding and their effects on stimuli processing. In addition, these findings reinforce the idea of the pupil old/new effect as a reliable measure of recognition memory as it remained consistent irrespective of attentional lapses due to mind-wandering and boredom.

Keywords: Mind-wandering, boredom, pupil old/new effect, recognition memory, eye-tracking.

Forget me (not): boredom impairs recognition memory but not the pupil old/new effect

Introduction

Imagine yourself learning a new language. You are sitting in class, paying attention, and taking notes. After some time, you suddenly “wake up” and realize that you lost focus and were thinking about something else, like your past interactions with people or future plans about what to make for dinner. This mental activity is called mind-wandering. Mind-wandering is the ability to disengage from the here and now and to mentally time travel to past or future events. Research shows that people spend around 25% to 50% of the day mind-wandering (Killingsworth & Gilbert, 2010; Klinger & Cox, 1987). This phenomenon is closely intertwined with episodic memory, which is generally defined as the capacity to recollect personally experienced events in subjective space and time (Baddeley, 2001; Tulving, 1993). Notably, mind-wandering can interfere with memory encoding and contribute to subsequent memory retrieval impairment (Martarelli & Ovalle-Fresa, 2023). The central role of attention in the encoding process has been highlighted by experimental research on memory and divided attention, as well as memory and selective attention (Aly & Turk-Browne, 2017).

Mind-wandering has been shown to have both positive and negative consequences. Positive consequences include relief from boredom (Mooneyham & Schooler, 2013), improving bad moods (Ruby et al., 2013), increasing positive emotions (Franklin et al., 2013), creative problem solving (Baird et al., 2012), and self-distraction (Lu et al., 2017), to mention a few. With respect to negative consequences, mind-wandering has been linked to impaired cognitive processes, such as vigilance (Schooler et al., 2011; Smallwood & Schooler, 2006), reading comprehension (Reichle et al., 2010; Schooler et al., 2004), cognitive task performance (e.g., slower reaction times; see McVay & Kane, 2012a), or working memory capacity (McVay & Kane, 2009, 2012b). Mind-wandering can also interfere with the memory encoding process and has been shown to negatively predict memory performance (Blondé et al., 2022a; Martarelli & Ovalle-Fresa, 2023; Riby et al., 2008; Seibert & Ellis, 1991).

Boredom is closely associated with mind-wandering; however, the exact line of separation between the two is not yet clear. Boredom has been defined as a state of inadequate function utilization, which can occur when the ongoing activity does not align with personal preferences, abilities, or energy levels (Wolff et al., 2024). Positive associations between mind-wandering and boredom have been reported in several studies outside the field of memory research (e.g., Carriere et al., 2008; Isacescu et al., 2017; Steinberger et al., 2016). Indeed, mind-wandering and boredom are inextricably linked; as an example, it has been suggested that mind-wandering is associated with reducing dissatisfaction related to boredom by redirecting attention to internal thoughts (Martarelli et al., 2021). Similarly, other researchers (Mittner et al., 2016), suggested that low arousal states, such as boredom, can prompt a shift from on-task to off-task states, triggering exploration behaviors, such as mind-wandering, which is exploited to temporarily relieve boredom. These findings suggest the need to assess both mind-wandering and boredom in an effort to shed further light on their dynamics and relative impacts on episodic memory (Martarelli & Baillifard, 2024). However, the dissociation of their respective effects on memory has only rarely been addressed with Blondé et al. (2022b) work standing as an exception.

In their experimental design, Blondé et al. (2022b) implemented an incidental encoding task interrupted by thought probes about mind-wandering and boredom.

The results showed a prominent correlation between mind-wandering and boredom; however, mind-wandering was a better predictor of item recognition than boredom. They reported that mind-wandering during encoding was negatively correlated with the subsequent item recognition.

This effect is consistent with the *perceptual decoupling hypothesis*, which suggests that mind-wandering shifts attention away from the task at hand to internally oriented cognition, thereby reducing the amount of perceptual input (Kam & Handy, 2018; Smallwood & Schooler, 2006). Perceptual decoupling is usually explained by the inability of working memory to inhibit the interference of task-unrelated thoughts (McVay & Kane, 2010). This implies that mind-wandering is a resource-demanding phenomenon, during which the perceptual input is attenuated but not entirely eliminated, which in turn can affect memory encoding.

With respect to memory assessment during mind-wandering, a typical approach involves a reading task or a task with controlled encoding and recognition phases (see, e.g., the studies of Feng et al. [2013] for a reading task, and Smallwood et al. [2004] for an encoding and retrieval task). Encoding can be intentional or incidental; the latter entails a lack of cognitive effort to remember information, which can elicit more mind-wandering. Surprisingly, previous studies investigating the impact of mind-wandering on memory performance have mainly used explicit memory tasks (i.e., participants were instructed that their memory performance would be assessed later). However, in mind-wandering research, it could also be beneficial to use incidental memory tasks, as they can increase the occurrence of mind-wandering, and because incidental memory is more prominent in daily life, as people spend less time deliberately learning information (Vingerhoets et al., 2005). Indeed, incidental task paradigms include stimuli that can trigger associations in thoughts. As participants do not necessarily use sustained attention to consciously focus on and remember stimuli, this paradigm might elicit more mind-wandering than intentional encoding (as argued by Maillet & Schacter, 2016).

As mind-wandering is an internal process without clearly defined visible cues, thought-probe methods are the most common approach to tracking it (Smallwood & Schooler, 2006; Weinstein, 2018). Interrupting individuals at random moments during an experimental task (e.g., a reading task) and asking them to report the content of their thoughts (whether they are thinking about the task or something else) is one of the easiest methods to assess mind-wandering. Apart from probing participants on the depths of their mind-wandering with Likert-type scales, it can also be beneficial to distinguish between different types of mind-wandering. As an example, stimulus-dependent and stimulus-independent mind-wandering (as explained by Stawarczyk et al., 2011) can affect memory performance differently. Stimulus-dependent mind-wandering, being related to the task at hand (i.e., thoughts that are elicited by stimuli of the task or the difficulty of the task) can facilitate memory performance (Maillet et al., 2017; Maillet & Schacter, 2016). In contrast, stimulus-independent mind-wandering (i.e., thoughts that are elicited by inner experiences or external distractors) can obstruct encoding and, subsequently, later recognition memory.

Despite the obvious benefits of using thought probes, they have been criticized for their potential influence on the frequency of mind-wandering (Seli et al., 2013). Others have suggested that this method may offer a possibly inaccurate reflection of inner states, as it requires a certain capacity for meta-awareness (Konishi & Smallwood, 2016) and depends solely on the subjective opinion of the participant (Kane et al., 2021). The probe rate (i.e., the number of options available for the answer) and terminology used (e.g., mind-wandering, task-unrelated thoughts, off-task thoughts, or mind-blanking) can also alter the participants' responses (Kane et al., 2021). This poses a question about the validity of subjective measures of mind-wandering, which is why it is beneficial to use probes with other objective measures of mind-wandering for additional support.

Other indirect measures for assessing the costs associated with mind-wandering include assessment of task performance, such as by evaluating the decline in classical sustained attention to response task (SART) performance (McVay & Kane, 2009; Smallwood et al., 2008) or reading comprehension (Unsworth & McMillan, 2013); both of these activities have been correlated with an increase in mind-wandering frequency. Moreover, mind-wandering can be assessed by physiological measures, such as brain activity (Christoff et al., 2009; Smallwood et al., 2008; Weissman et al., 2006), skin conductance and temperature (Blanchard et al., 2014), heart rate (Pham & Wang, 2015), and eye behavior, which includes changes in pupil size (Grandchamp et al., 2014; Smallwood et al., 2011), blink rate (Smilek et al., 2010), eye gaze (Hutt et al., 2019), fixations, saccades (Grandchamp et al., 2014) and, finally, gaze patterns (Zhang et al., 2021). In fact, thought probes during different tasks have been moderately correlated with these different parameters (Kane et al., 2021), however, these measures have also been reported to capture correlated factors including drowsiness (Stawarczyk et al., 2020).

In this registered report, we aimed to investigate the relationship between mind-wandering and boredom during encoding, assessed with thought probes during encoding, and pupillometry during recognition. As previous findings of explicit measures have indeed linked both mind-wandering and boredom to poorer memory (Blondé et al., 2022b; Carriere et al., 2008), our study introduces a novel perspective by incorporating indirect measures into the investigation (pupillometry during both encoding and recognition phases). Pupillometry was first introduced in psychology as a measure of emotional processing by Hess and Polt (1960), followed by pioneering investigations into the connection between pupil size and memory load by Kahneman and Beatty (1966), which is relevant to the current work. They found that pupil diameter is a measure of the active processing of material during short-term memory tasks (Kahneman & Beatty, 1966). Further research has found that the pupillary response reflects a broad spectrum of cognitive reactions and processes, such as perceptual selection (Einhäuser et al., 2008), cognitive load (Beatty, 1982; Gavas et al., 2017; Jainta & Baccino, 2010), memory encoding and retrieval (Otero et al., 2011; Papesh et al., 2012), and arousal during the affective processing of visual stimuli (Murphy et al., 2014; Nassar et al., 2012).

In a study investigating the influence of emotional content on memory performance via pupillometry response, Võ et al. (2008) found that pupil dilation starts in the first few hundred milliseconds after the onset of cognitive effort to retrieve information, which explains the delay in the reaction of the pupil to old stimuli. This phenomenon of increased pupil dilation in response to old stimuli compared to new stimuli, has been termed the “pupil old/new effect” by Võ et al. (2008). Larger pupil dilation in response to old stimuli versus new stimuli was also found in studies conducted by Kafkas and Montaldi (2011, 2015, 2018) and Papesh et al. (2012). Possible explanations for the pupil old/new effect include cognitive effort that is associated with memory recognition processes (Võ et al., 2008) or the strength of the memory trace upon which we make the judgment of recognition (Otero et al., 2011).

To our knowledge, the pupil old/new effect has not been used as a neurocognitive marker of the effects of mind-wandering and boredom on recognition memory. Here, we aim to investigate the following research question: can the pupil old/new effect track the impact of mind-wandering and boredom on recognition memory? Specifically, we intend to examine the impact that mind-wandering and boredom (during the encoding of information) has on the pupil old/new effect (during recognition). We hypothesize that the more on task participants remain during encoding, the bigger the pupil old/new effect will be during recognition. Furthermore, based on Blondé et al. (2022b), we expect mind-wandering to be a more influential predictor than boredom. For more extensive explorative analyses we plan to record and analyze eye parameters during encoding of information.

This project has the potential to advance research on the objective markers of mind-wandering and boredom, which, in turn, can shed more light on the mechanisms underlying them. The novel approach of dissecting the effects of mind-wandering and boredom on the pupil old/new effect can provide useful insights on attention and engagement. The use of eye-tracking is non-invasive and relatively cost-effective in comparison with other techniques like neuroimaging or EEG for detecting mind-wandering and its effect on memory. By examining eye behavior in addition with recognition memory performance, we can potentially detect mind-wandering in a more comprehensive way. This dual approach can provide more insight into our cognitive processes and help amplify the subjective self-report data.

Method

Proposed sample size

We based the required sample size calculation on previous studies investigating the pupil old/new effect (see Table 1, where effects range from medium to large), specifically, on the closest study to our design and materials by Ring et al. (2020), who studied 30 individuals with typical development and found a significantly larger pupil size for old compared to new stimuli for individuals with typical development (p < .0001, Cohen's d = 0.42, 95% CI [−0.10, 0.93]). Based on this effect size, an a priori G*Power analysis suggested that a sample size of 63 participants is needed to detect an effect of 0.42 (one-tailed paired-sample t-test, input parameters: d = 0.42, α = 0.05, 1−β = .95; Faul et al., 2007).

Table 1

Small review of publications on the pupil old/new effect

Publications	**Number of participants**	**Stimuli**	**Effect size of the pupil old/ new effect**
Heaver & Hutton (2011)	26	Semantic: visual representation of the words	n^2p = .65 (large effect)
Montefinese et al. (2013)	20	Semantic: visual representation of the words	n^2p = .04 (medium effect)
Oliveira et al. (2021)	42	Semantic: visual representation of the words	n^2p = .145 (large effect in the shortest retention interval)
Otero et al. (2011) 2nd experiment	34	Auditory	n^2p = .423 (large effect)
Otero et al. (2011) 3rd experiment	35	Semantic: visual representation of the words	n^2p = .325 (large effect)
Ring et al. (2020)	27 autism spectrum disorder adults (ASD) and 30 typical development (TD) individuals	Visual (pictures, shapes) and semantic (words, non-words)	Cohen's d = 0.42 (medium effect)

Note: This table presents five relevant publications of six experiments reporting on the pupil old/new effect, as well as the number of participants, the stimuli used in the experiment, and the effect size.

Participants

As preregistered, we collected data from healthy adults aged 16–40 years at our laboratory in Brig (Switzerland). Participants were recruited through the online participant pool of UniDistance Suisse, which includes students of UniDistance, as well as members of the general population who express interest in participating in the studies. Participants were informed about the remuneration of 25 CHF/hour for participation in the experiment. Participants were able to stop the experiment at any moment and request the deletion of their data. The local ethics committee approved the study, which was conducted according to the WMA Declaration of Helsinki regarding ethical principles for medical research.

All participants successfully completed the calibration and validation procedures for eye-tracking (average horizontal and vertical error smaller than 0.7° angular accuracy), experienced mind-wandering and boredom (none of the participants reported absence of mind-wandering or boredom), and succeeded at the semantic task during the encoding (more than 80% of correct categorization). One participant was excluded from the analysis for deliberate memorization of stimuli in the incidental memory task during encoding, as he indicated so in the questionnaire at the end of the experiment (see Appendix for the questionnaire). No further exclusions were made. The final sample consisted of 64 participants ranging from 16 to 38 years old ($M = 21.31$, $SD = 4.91$, 77% women), most of them (70.31%) full time students.

Apparatus and stimuli

The experiment was conducted with the use of the Experiment Builder program, which is directly linked to the eye-tracker (EyeLink 1000 Plus, SR Research Ltd.) and designed for computer-based psychology experiments. The eye-tracker recorded the eye behavior with an infrared illuminator; data was registered with a sampling rate of 1000 Hz, a spatial resolution of 0.01°, and a gaze position accuracy of 0.5°. The stimuli were presented on the computer display of 1920 × 1080 pixels via the EyeLink Desktop Mount at a range of 45 cm from the participants' head.

Participants underwent a 9-point grid calibration, followed by a 10-point grid validation before each experimental phase.

For stimuli material during the incidental memory task, we used pictures of simple everyday objects from the Bank of Standardized Stimuli (BOSS). As the human eye is sensitive to light and eye position changes, we transformed the stimuli into greyscale using the "Imager" (_imager, Barthelme, 2023) image process library in R (R Core Team, 2022). Although recognition of colorless stimuli might be somewhat less likely than recognition of colored stimuli (Dzulkifli & Mustafar, 2013), controlling the amount of visual information is crucial when investigating the pupil old/new effect, as the light and stimuli intensity can introduce variations in the pupil size (Ellis, 1981). As the pupil old/new effect was found to be the most prominent for neutral stimuli, compared to the diminished effect for emotional stimuli (Brocher & Graf, 2016, experiment 2; Võ et al., 2008), we used normative stimuli from the BOSS database. We deleted similar stimuli from each category to avoid strong associations between them (e.g., "boat," "cruiseship," and "sailboat"). To minimize fluctuations in pupil size, we asked participants to fix their eyes on a fixation cross before each trial. Moreover, the stimuli were presented centrally with a size of 300 × 300 pixels (about 8 × 8 cm).

Procedure

The experimental session included an encoding phase and a recognition phase (see Figures 1 and 2). Prior to the experiment, the instructors explained to the participants what mind-wandering is and its types (stimulus-dependent/stimulus-independent), what boredom is, and instructed them to be aware of their mental states.

<u>Encoding phase.</u> The encoding phase included 275 stimuli. Each stimulus started with a fixation cross on the screen for 500 ms, followed by an encoding

screen with the visual stimuli presented for 3 s in the center of the screen. In order to ensure incidental encoding of task stimuli, we have included a semantic judgement task in the encoding phase of the experiment. In this task participants were asked to reply to the question “Is this object natural or man-made?” The question was presented on a separate screen after each picture trial, and stayed on the screen until a response was made, the latency of which was tracked for further analyses.

Apart from 275 stimuli and semantic questions in the encoding phase, participants were presented with thought probes about mind-wandering, a mind-wandering type question, and boredom probes. Mind-wandering (i.e., “How much are you mind-wandering right now?”) and boredom probes (i.e., “How bored are you right now?”) were presented after every five to 16 encoding screens in a pseudorandomized order to avoid predictions about the question being established. Participants used the left and right arrows on the keyboard to answer the questions. The mind-wandering scale ranged from 0% (“Completely on task”) to 100% (“Completely off task”), which was successfully implemented in Brosowsky et al. (2021; for a continuous scale of mind-wandering, see also Martarelli & Ovalle-Fresa, 2023). If participants’ answer to the mind-wandering probe was from 0% - 49% range, they continued with encoding, if their answer fell into 50% - 100% range, they received the question about the type of mind-wandering they have experienced. The mind-wandering type probe included the question, “What type of mind-wandering did you just experience?” with a dichotomous stimulus-dependent/stimulus-independent answer; participants had to press a left arrow button for stimulus-dependent and a right arrow button for stimulus-independent mind-wandering (or vice versa; the design was counterbalanced). The continuous scale in boredom probes (“How bored are you right now?") also ranged from 0% ("not at all bored") to 100% ("completely bored"). Any answer to the boredom probe entailed continuation with the task.

We tracked pupil behavior during encoding for explorative analyses of the pupil size changes associated with mind-wandering and boredom during encoding. The encoding phase took around 30 minutes.

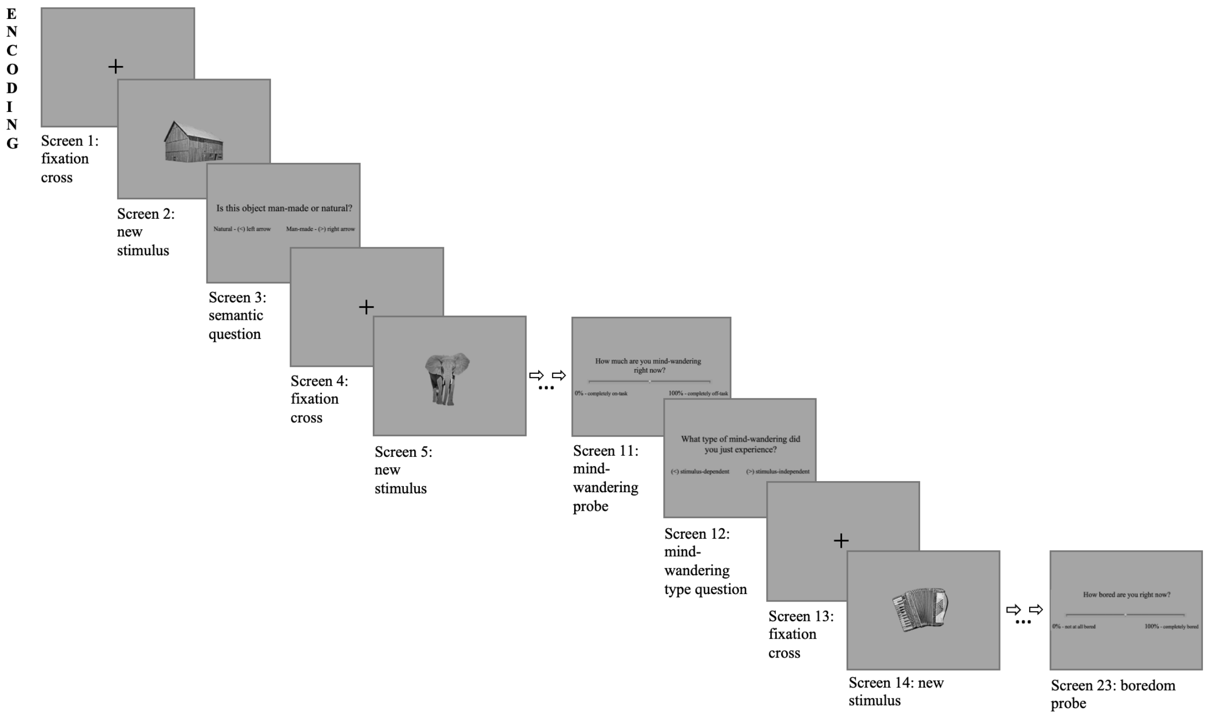

Figure 1. Visual representation of the encoding phase. The encoding phase consisted of the incidental memory task. During *encoding,* 275 stimuli were presented for 3 s, separated by a fixation cross for 500 ms after each stimulus. Stimuli were interrupted by mind-wandering and boredom probes, which appeared each five to 16 screens in a pseudorandomized order, with the question "How much are you mind-wandering right now?" or "How bored are you right now?" to be answered on a continuous scale ranging from 0% to 100%. If participants chose 0% - 49% on the mind-wandering probe, they continued with encoding. If participants chose 50% - 100%, they were prompted by a mind-wandering type question, "What type of mind-wandering did you experience?" with dichotomous stimulus-dependent or stimulus-independent answers, then continued with encoding.

Recognition phase. The recognition phase took place after the encoding phase and included 550 stimuli overall, including 275 new stimuli (BOSS stimuli that were not shown in the encoding phase) and 275 old stimuli (BOSS stimuli that were shown in the encoding phase) presented for 2 s in randomized order, during which we tracked the pupil size for the pupil old/new effect. We deemed a 2 s trial length sufficient for tracking the pupil change, as it has been successfully implemented in previous research (Heaver and Hutton, 2011, Otero et al., 2011 (experiment 1 and 3) and Võ et al., 2008). Recognition memory was tested with a question ("Is this an old or new picture?") that was presented right after every picture screen, on the next empty gray screen with "old/new" as dichotomous response options. To answer the question, participants pressed the left arrow button for "old" and the right arrow for "new" or vice versa in the counterbalanced version of the experiment. The recognition phase took about 35 minutes to complete. After the experiment, the participants were asked to fill out a questionnaire about their demographic information (see Appendix for the questionnaire).

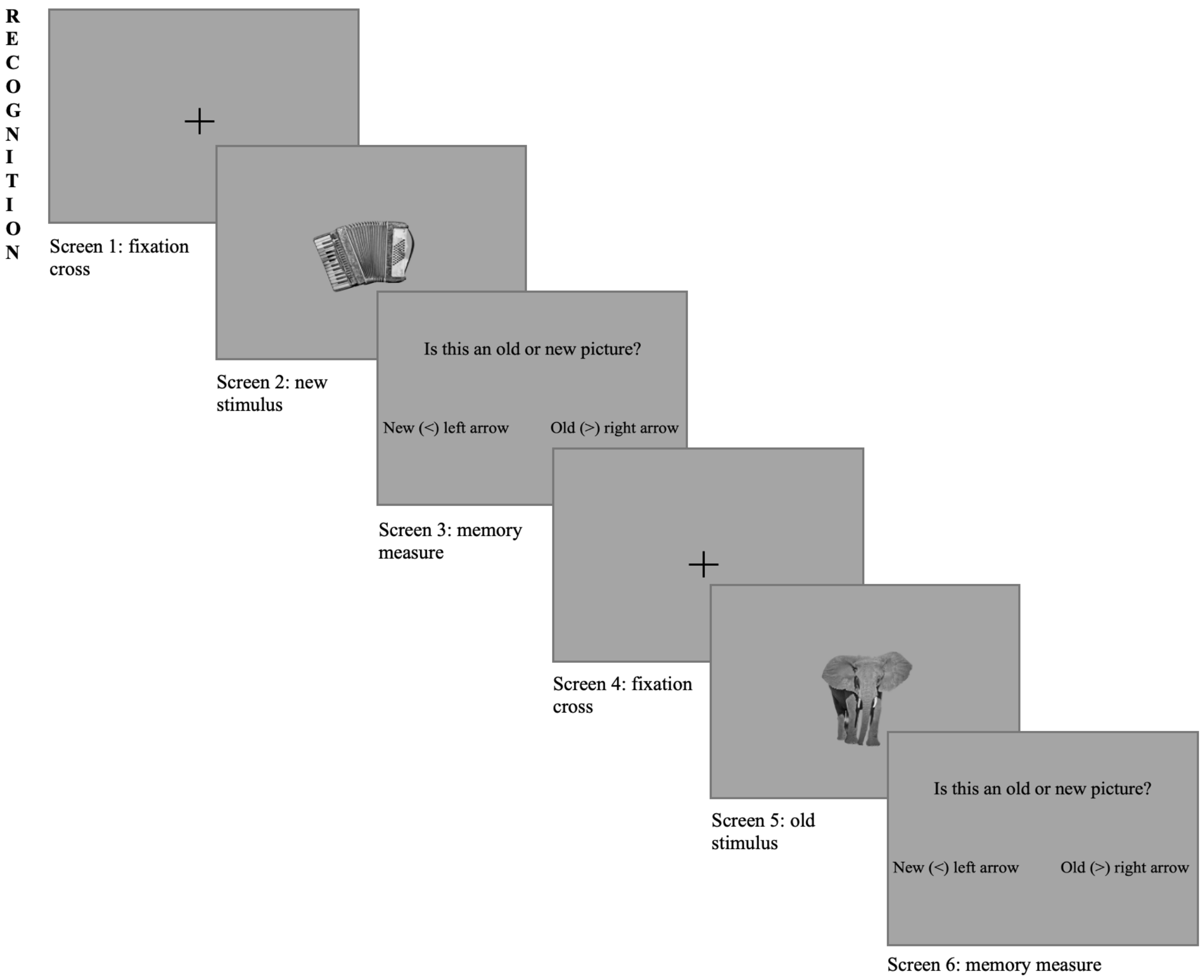

Figure 2. Visual representation of the recognition phase. During the recognition phase, 550 stimuli (275 shown in the encoding and 275 new) were randomly presented on the screen for 2 s, separated by a fixation cross for 500 ms, and followed by a recognition question, "Is this an old or new picture?" after each stimulus.

Results

All data were analyzed with lme4 package (Bates et al., 2015) in R (R Core Team, 2022). Data were exported using the EyeLink Data Viewer software package (SR Research Ltd., version 4.2.1). Blinks were automatically excluded by the program. We used signal detection theory (Stanislaw & Todorov, 1999) to assess accuracy of participants' responses in the recognition phase of the experiment, with the following formula: $d' = z(H) - z(FA)$, where H is the proportion of old stimuli correctly identified as old to the number of overall old items presented, *FA* is the proportion of old stimuli incorrectly identified as new to the number of overall new items presented, and *z* is the *z*-score of hits and false alarms ratios. We used generalized linear mixed models (GLMMs) to analyze the data, which allows for flexibility and treatment of both categorical and continuous variables (Baayen et al., 2008). The approved Stage 1 protocol can be found on OSF (https://osf.io/gue36). The full non-aggregated dataset and the analysis code is available on OSF (https://osf.io/ge4a9/).

Descriptive statistics

Task performance in the semantic task (during the encoding phase)

During the semantic task during the encoding phase of the experiment, participants were accurate in 95.23% of trials (*SD* = 21.32%). In line with our expectations, accuracy was high, demonstrating participants' sufficient attention to the stimuli for incidental encoding.

Recognition memory performance in the old/new task (during the recognition phase)

During the recognition memory task, participants were accurate in 75.69% of trials (*SD* = 42.9%). Mean recognition memory performance (d'prime) was 1.77 (*SD* = 0.49), reflecting an overall strong ability of participants to discriminate between old and new stimuli during the recognition phase of the experiment.

Pupil old/new effect

The pupil old/new effect was calculated as the difference between baseline corrected maximal pupil sizes for old stimuli during recognition and baseline corrected maximal pupil sizes for new stimuli during recognition. The raw pupil old/new effect (in pixels) was 11.89 (*SD* = 11.51, $t = 8.259$, $p < 0.001$), indicating significant larger pupil sizes for old stimuli than for new stimuli during recognition. The effect size of the measure was calculated with Cohen's d_z with the following formula $d_z = (mean_1 – mean_2)/ \sqrt{(sd^2_1 – sd^2_2)}$ (Cohen, 1988). The effect size of the pupil old/new effect was 0.25 with a 95% CI [-0.004, 0.503], indicating a small to medium difference between pupil sizes for old and pupil sizes for new stimuli during recognition. A graphical representation of the pupil old/new effect was not preregistered, but we think it is complimentary to the text description (see Figure 3).

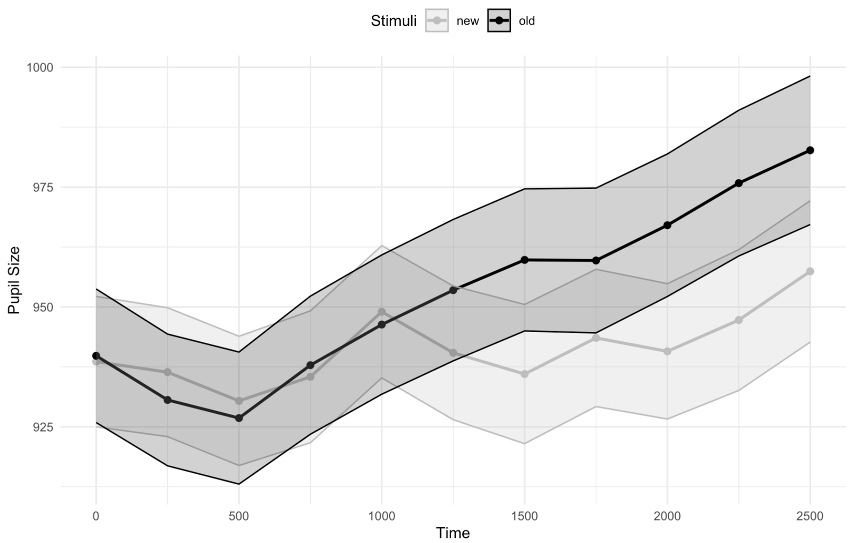

Figure 3. Pupil size for old and new stimuli during the recognition phase of the experiment. The y-axis represents the average pupil size (in pixels), the x-axis indicates the time course of the trial (in milliseconds). A fixation cross was displayed for the first 500 ms, followed by

the stimulus presentation from 500 ms to 2500 ms. The black line indicates pupil size for old stimuli, the light grey line indicates pupil size for new stimuli. Shaded areas around the lines represent the 95% confidence interval.

Self-reports of mind-wandering and boredom (during the encoding phase)

On average, participants were mind-wandering in 44.14% (*SD* = 26.66%) of the trials during the encoding. Of this, 40.3% was stimulus-dependent mind-wandering and 59.7% stimulus-independent. In terms of boredom, participants indicated being bored in 43.93% of the trials (*SD* = 28.81%). Graphical representations of mind-wandering and boredom were not preregistered; however, we consider them complementary to the text description and useful for showing the progression of mind-wandering and boredom levels with the time course of the encoding phase (see Figure 4).

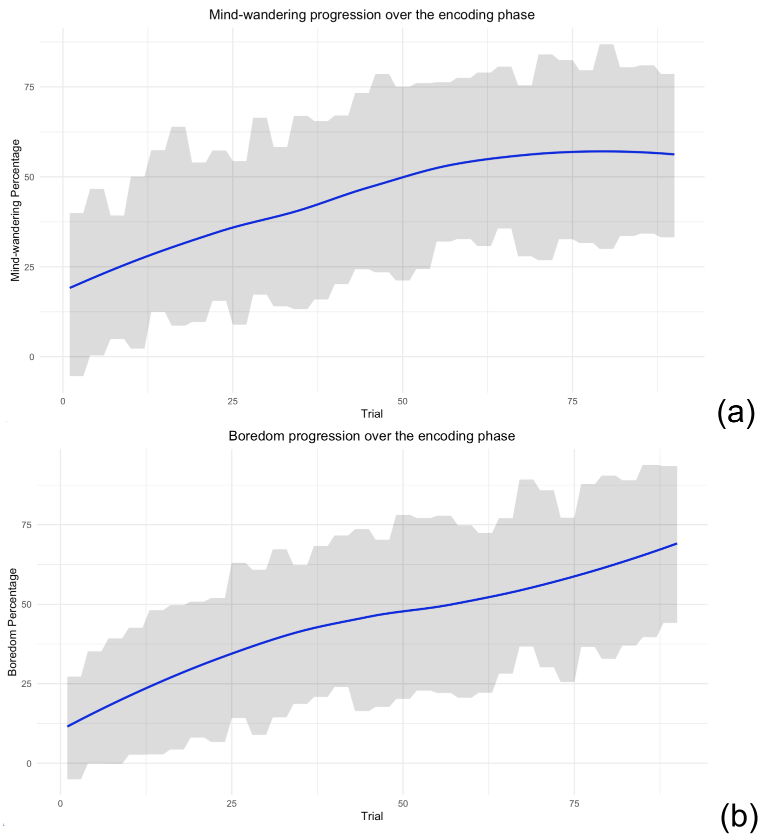

Figure 4. Progression of mind-wandering (a) and boredom (b) over the course of encoding. The x-axis represents the trial progression throughout the task, the y-axis represents the mind-wandering and boredom percentages respectively, grey shaded area represents one

standard deviation above and below the mean across all participants for each trial. Data were fitted with Loess (Locally Estimated Scatterplot Smoothing) regression.

Analyses of mind-wandering and boredom effects on recognition memory

During the recognition phase, participants were presented with 250 old (previously seen) stimuli and 250 new stimuli. We focused our analysis on the three trials preceding the thought probes (time window of 10.5 seconds). Data was combined from thought probes and memory accuracy for the old stimuli. This resulted in final datasets of 90 trials per person. Mind-wandering and boredom probes during the encoding phase of the experiment were separated, thus, statistical analyses for mind-wandering and boredom had to be done separately. All models included *accuracy of participants' responses* during the old/new recognition task as the dependent variable (binary outcome, correct ("old" answers for old stimuli and "new" answers for new stimuli) vs. incorrect ("new" answers for old stimuli and ("old" answers for new stimuli)), represented by log-odds of a correct response. All models included by-participant random intercept and random slope. We standardized the predictors. We report R^2 and R^2_c (conditional) to compare the models.

Impact of mind-wandering on recognition memory

In the first model, we took *accuracy of participants' responses* during the old/new recognition task as the dependent variable with *mind-wandering percentage* (continuous measure of on-task vs. off-task) as predictor. The analysis did not show a significant effect of mind-wandering on recognition accuracy (*estimate* = - 0.129, *p* = 0.101, R^2 = 0.0045, R^2_c = 0.098).

Impact of mind-wandering type on recognition memory

In the second model, we took *accuracy of participants' responses* as the dependent variable with *the mind-wandering type* (binary measure: stimulus-dependent vs. stimulus-independent) as predictor. The analysis did not show a significant effect of mind-wandering type on recognition accuracy (*estimate* = 0.078, *p* = 0.6, R^2 = 0.0004, R^2_c = 0.077).

Impact of boredom on recognition memory

The third model included *accuracy of participants' responses* as the dependent variable with *boredom percentage* (continuous measure) as predictor. The analysis revealed a significant effect of boredom on recognition accuracy (*estimate* = -0.136, *SE* = 0.065, *z* = -2.08, *p* = 0.038, 95% *CI* [-0.259, -0.016], R^2 = 0.005, R^2_c = 0.097), indicating that an increase in boredom was associated with a decrease in recognition accuracy (see Figure 5).

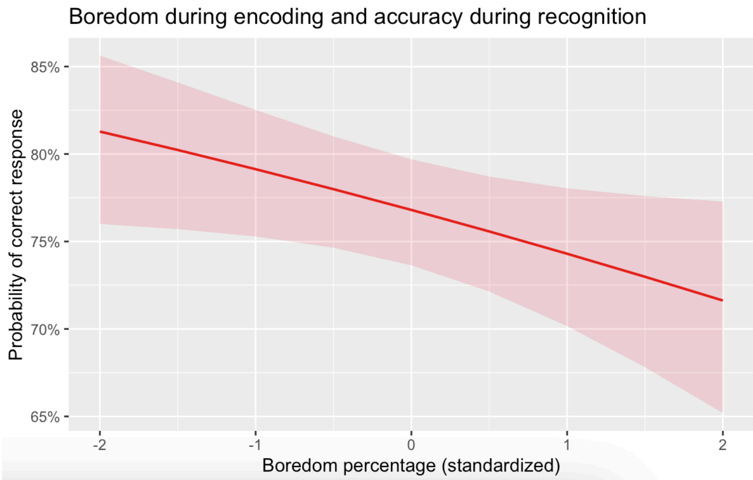

Figure 5. Effect of boredom during encoding of stimuli on recognition memory. The figure illustrates the relationship between boredom percentage (standardized) during the encoding phase of the experiment and the probability of correct responses during the recognition phase of the experiment. The red line indicates the predicted probability of correct response (in percentages), and the red shaded area indicates the 95% confidence interval.

Analyses of mind-wandering and boredom effects on the pupil old/new effect

All models included the pupil old/new effect (as the difference between baseline corrected old and new pupil sizes in recognition) as a dependent variable, as well as by-participant random intercept and random slope. We report semi-partial R^2 to compare the individual effects of each predictor included in the models.

Impact of mind-wandering on the pupil old/new effect

The first model included *the pupil old/new effect* as dependent variable, *mind-wandering percentage*, *accuracy* during the old/new recognition task (log-odds of a correct response), as well as the interaction *mind-wandering percentage by accuracy* as predictors. The model showed a significant effect of recognition accuracy on the pupil old/new effect (*estimate* = 14.04, *SE* = 5.53, $t = 2.54$, $p = 0.014$, semi-partial R^2 = 0.003), indicating that higher recognition accuracy was associated with a bigger pupil old/new effect. The effect of mind-wandering on the pupil old/new effect was not significant (*estimate* = 0.502, $p = 0.904$, semi-partial $R^2 < .001$). The interaction between mind-wandering and recognition accuracy was not significant as well (*estimate* = -5.107, $p = 0.296$, semi-partial $R^2 < .001$).

Impact of boredom on the pupil old/new effect

The second model included the *pupil old/new effect* as dependent variable, *boredom percentage* and *accuracy* during the old/new recognition task (log-odds of a correct response) as predictors. The model showed a significant effect of recognition accuracy on the pupil old/new effect (*estimate* = 19.03, *SE* = 4.36, $t = 4.369$, $p < 0.001$, semi-partial $R^2 = 0.0067$). This result suggests that higher recognition accuracy was associated with a bigger pupil old/new effect. The estimated effect of boredom on the pupil old/new effect was insignificant (*estimate* = -0.794, $p = 0.833$, semi-partial $R^2 < .001$). The interaction between boredom and recognition accuracy was not significant as well (*estimate* = 0.919, $p = 0.829$, semi-partial $R^2 < .001$).

Exploratory analyses

In this section we report exploratory analyses between different eye parameters. To account for individual changes in pupil size, we baseline-corrected the pupil size during encoding. This correction entailed subtracting the maximal pupil size during a 500 ms fixation cross before each picture trial from the maximal pupil size during the picture trial, a method successfully employed in previous studies (Bradley & Lang, 2015; Campos-Arteaga et al., 2020; Kafkas & Montaldi, 2015).

Exploratory analysis of pupil parameters correlations during encoding

We found significant correlations between eye parameters during the encoding: number of fixations was positively correlated with number of blinks (*r* = 0.30, *p* = 0.014), number of blinks was negatively correlated with average fixation duration (*r* = -0.44, *p* < 0.001) and maximal fixation duration (*r* = -0.50, *p* < 0.001); number of fixations were negatively correlated with the maximal fixation duration (*r* = -0.85, *p* < 0.001); average fixation duration was positively correlated with maximal fixation duration (*r* = 0.95, *p* < 0.001) (see Table 2 below).

Table 2

Descriptive statistics and correlations for mind-wandering during encoding and encoding parameters

Variable	M	SD	1	2	3	4	5	6	7	8	9	10
1. Recognition accuracy (recognition task) (percentage)	76	0.11	—									
2. Mind-wandering percentage	44.4	20.08		—								
3. Boredom percentage	43.75	21.65			—							
4. Pupil size during encoding (pixels)	92.41	44.19	-0.17	0.24	0.14	—						
5. Reaction times (semantic task) (ms)	692.68	295.11	-0.1	**0.36****	**0.28***	**0.39****	—					
6. Performance (semantic task) (percentage)	95	0.07	0.07	0.01	-0.03	0.15	0.04	—				
7. Number of blinks	1.18	0.87	0.01	0.18	**0.30***	0.01	0.02	-0.06	—			
8. Number of fixations	6.47	1.15	0.12	-0.03	-0.15	0.12	-0.19	-0.05	**0.30***	—		
9. Average fixation duration	494.84	166.06	-0.05	-0.02	-0.02	-0.05	0.23	0.02	**-0.44*****	**-0.83*****	—	
10. Maximal fixation duration	964.07	236.46	-0.04	-0.03	0.01	-0.04	0.14	0.10	**-0.50*****	**-0.85*****	**0.95*****	—

Note: the table presents means, standard deviations and Pearson correlation coefficients (*r*) for relationships between accuracy during the recognition task, mind-wandering percentage during encoding, boredom percentage during encoding, reaction times during the semantic task, performance on the semantic task and pupil parameters during encoding (pupil size, number of blinks, number of fixations, average fixation duration, and maximal fixation duration). *Pupil size during encoding* variable is baseline corrected. *Number of fixations* and *maximal fixation duration* variables are averaged per one trial. $p < 0.1$, *$p < .05$, **$p < .01$, ***$p < .001$.

Exploratory analysis of mind-wandering and boredom during encoding and eye parameters

In the exploratory analyses of mind-wandering, boredom and encoding parameters (see Table 2 above), pupil size during the encoding (baseline corrected) was positively correlated with reaction times during the semantic task ($r = 0.39$, $p = 0.001$). Mind-wandering and boredom both were positively correlated with reaction times during the semantic task ($r = 0.36$, $p = 0.004$; $r = 0.28$, $p = 0.024$). Further, boredom was positively correlated with the number of blinks ($r = 0.30$, $p = 0.018$).

Exploratory analyses of variables in the encoding phase of the experiment in relation to subsequent memory recognition

We found no correlation of pupil parameters during the encoding (pupil size, number of blinks, number of fixations, maximal fixation duration) with accuracy of participants' responses during the recognition phase of the experiment (see Table 2 above).

Pupil size during encoding and recognition memory (not preregistered)

Due to the lack of significant correlation between pupil size during encoding and accuracy of participants' responses during recognition (see Table 2), which contradicts existing literature (Kafkas & Montaldi, 2011; Kucewicz et al, 2018; Naber et al., 2013), we conducted a mixed model analysis (not preregistered) with random slopes and intercepts to account for the temporal structure. In line with previous findings, we found a significant effect (*estimate* = -0.108, *SE* = 0.040, *z* = -2.67, *p* = 0.008, 95% CI [-0.183, -0.028], R^2 = 0.003, R^2_c = 0.090), indicating that smaller pupil size during encoding was associated with better accuracy during recognition (see Figure 6).

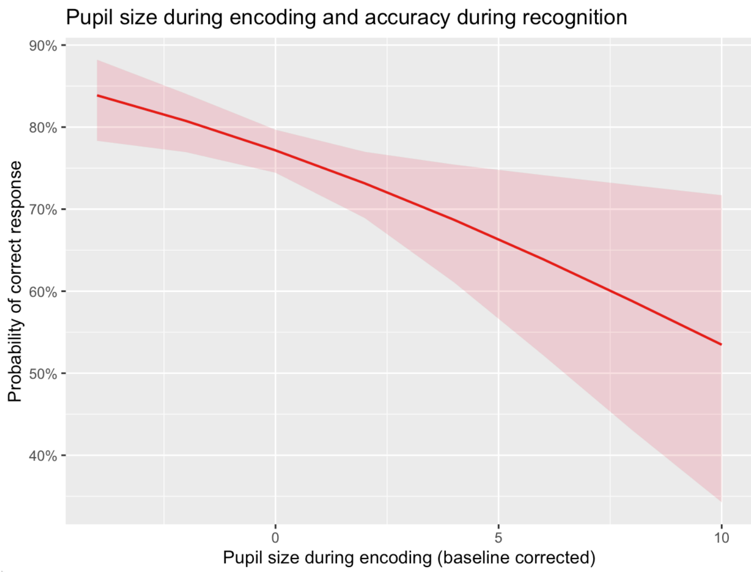

Figure 6. Effect of pupil size during encoding on accuracy during recognition. The figure illustrates the relationship between pupil size (standardized) during the encoding phase of the experiment and the probability of correct response (in percentages) during recognition phase of the experiment. Red line indicates the predicted probability of correct response and red shaded area indicates the 95% confidence interval.

Discussion

In this study we examined the effect of mind-wandering and boredom on memory and the pupil old/new effect by employing an incidental memory task with mind-wandering and boredom probes, and an old/new recognition task. Firstly, we expected both mind-wandering and boredom during stimuli encoding to impair recognition memory, and we expected mind-wandering to be a stronger predictor of recognition memory than boredom. Secondly, we expected that mind-wandering and boredom during stimuli encoding would impact the pupil old/new effect during recognition. Again, we expected this effect to be more pronounced for mind-wandering than for boredom. Consistent with our hypotheses, our analyses revealed a significant effect of boredom during encoding on recognition memory. The results of our other analyses did not support our hypotheses: We found no support for the idea that mind-wandering affects recognition memory, as well as for the hypothesis that mind-wandering and boredom affect the pupil old/new effect. In the next sections, we discuss the results in the order in which the analyses were conducted.

We found no significant effect of mind-wandering during encoding on accuracy during the old/new recognition task. This non-finding may be attributed to the nature of the task itself. To our knowledge, no studies have used a semantic task as an incidental memory task for picture stimuli during encoding and an old/new task during recognition to investigate the effects of mind-wandering on recognition memory. It is possible that such an incidental task allows for automatic or unconscious encoding regardless of mind-wandering episodes. Recent studies have shown that mind-wandering does not hinder the encoding processes completely; instead, a gradual suppression of visual processing during encoding is suggested (Martarelli & Ovalle-Fresa, 2023; Groot et al., 2021). This low-level processing can stay intact during mind-wandering (as a state of weak decoupling; Schad et al. (2012) and allow for some shallow encoding of stimuli, which might be sufficient for successful recognition during an old/new recognition task. Research that uses this task to investigate the effect of mind-wandering on memory shows varying results. For example, Thomson et al. (2014) used intentional encoding of word stimuli during a semantic task (with stimuli size judgements as deep encoding, and stimuli case judgements as shallow encoding) and an old/new recognition task. They found a significant negative relationship between mind-wandering and recognition memory, but only for the deep encoding condition. In another study, Maillet and Schacter (2016) assessed effects of incidental encoding of picture and word stimuli during a semantic (manmade/natural judgements) task on an old/new recognition task that only used word stimuli. Here, they found that stimulus-dependent and independent thoughts did not predict recognition memory in young adults. Finally, in a study by Blondé et al. (2022b) with an incidental encoding of picture stimuli during an n-back task and a subsequent old/new recognition task, a significant negative effect of mind-wandering on recognition memory was found. These inconsistent results might be linked to different stimuli and varying instructions employed for the encoding parts of each experiment.

Interestingly, in the current study, the effect of boredom on recognition memory prevailed over the effect of mind-wandering, contradicting previous findings (hindering effect of mind-wandering on memory is superior to that of boredom, according to Blondé et al., 2022b) and our expectations. We hypothesize that during the incidental encoding task, boredom was associated with a deeper level of disengagement than mind-wandering - deep enough to inhibit memory encoding. In line with our findings, earlier research has attributed boredom to failures in attention and task engagement (Eastwood et al., 2012). Recent research helps explain how boredom hinders attention – it is suggested that boredom triggers exploration behaviour (Geana et al., 2016), driving attention away from the task at hand (Martarelli & Baillifard, 2024). Varying effects of mind-wandering and boredom on recognition memory found in this experiment further underline their differences in depth of disengagement and stimuli processing.

Our results did not support the hypothesis that the impact of mind-wandering or boredom on recognition memory can be detected with the pupil old/new effect. The pupil old/new effect during the recognition phase of the experiment was consistently present regardless of mind-wandering, boredom or their depth levels during the encoding. Mind-wandering and boredom are complex mechanisms; both can vary in duration and depth of disengagement, which might not have been effectively captured by the pupil old/new effect variations in our study. The pupil old/new effect, unaffected by mind-wandering and boredom, reflects an automated and, perhaps, unconscious encoding and processing of stimuli. Because of the low-level cognitive nature of pupil reactions, they can work independently of higher-level cognitive mechanisms like mind-wandering or boredom, which may not disrupt the visual processing of stimuli, as measured by the pupil old/new effect. Furthermore, the observed significant effect of recognition accuracy in the models suggests that higher accuracy was attributed to stronger task focus and engagement. It is worth noting that the pupil old/new effect has been observed regardless of correct or incorrect responses on the accompanying memory task (Herweg et al., 2018; Kafkas & Montaldi, 2015), regardless of whether participants were instructed to feign amnesia or report all stimuli as new (Heaver & Hutton, 2011). The fact that it is also unaffected by mind-wandering and boredom suggests that it is not fully under our conscious control. Pupil old/new effect, thus, could be considered not only a good measure of recognition memory (Lapteva & Martarelli, 2024), but also a good measure of visual processing, that can bypass the need for a memory response.

In line with previous findings (McVay & Kane, 2012a, Henríquez et al., 2016), we found a correlation of mind-wandering with reaction times during encoding, linking longer reaction times with deeper mind-wandering levels. Furthermore, reaction times were correlated with the pupil size during encoding, with slower reaction times related to increased pupil dilation (as in Oliva, 2019). During the semantic task, some picture stimuli might have been harder to categorize than others, which potentially caused participants to exhibit more effort. Both slower reaction times and increased pupil dilation separately have been correlated with an increase in cognitive effort (dilation in Kahneman & Beatty, 1966; reaction times in Robinson et al. 1997), which supports our interpretation.

Regarding the analyses of boredom and encoding parameters, we found a link between boredom and reaction times with an increase in boredom associated with slower reaction times. The association of boredom and delayed responses to stimuli categorization could relate to mental fatigue, induced by boredom. Indeed, previous research revealed that higher levels of fatigue (that are strongly related to higher levels of boredom; Dora et al., 2021), have been associated with increased reaction times in a go/no-go task (Kato et al., 2009). In addition, as boredom is understood to direct attention away from what one is currently doing (Wolff et al., 2024), it is plausible that people either slow down their responses or hurry through their current task (Bieleke et al., 2021).

Interestingly, boredom was positively correlated with the number of blinks in our study. Previous research found that high trait boredom was associated with higher blink rates (Danckert et al., 2018), however, to our knowledge, state boredom and number of blinks association had not yet been associated. Given that people blink less when viewing important content (Ranti et al., 2020), it is reasonable to suggest that with the progression of the task, participants perceived stimuli as less important, which was associated with an increased number of blinks. Furthermore, increasing levels of boredom associated with increased levels of fatigue (Dora et al., 2021), could in fact be linked to an increase in the number of blinks in our study (blink rate as a possible measure of fatigue - Stern et al., 1994).

We found no correlation between variables in the encoding phase of the experiment (pupil size, number of blinks, number of fixations, maximal fixation duration) and accuracy during the recognition phase of the experiment. However, a mixed model analysis of the pupil size during encoding and accuracy during recognition, consistent with previous research, revealed that smaller pupil size was associated with better recognition accuracy (also in Kafkas & Montaldi, 2011; Kucewicz et al., 2018; Naber et al., 2013). Decreased pupil size during encoding of items that are successfully recognized after is an interesting neurophysiological mechanism that is hypothesized to modulate memory processing by reducing arousal and restricting the focus of attention to stimuli encoding (argument from Kafkas & Montaldi, 2011). Our replication of this finding is important, as it suggests reliability of our data.

Conclusion

In this study we focused on investigating the effects of mind-wandering and boredom on recognition memory and on the pupil old/new effect in 64 participants. We used a semantic task as an incidental memory task for stimuli encoding, during which we probed participants about their mind-wandering and boredom levels; we used a surprise old/new recognition task to check the recognition memory, and throughout the whole experiment we tracked participants' eye behavior. Mind-wandering and boredom appeared to involve different depths of disengagement, with boredom showing a stronger effect on recognition memory compared to mind-wandering. The results also revealed the intricate nature of the pupil old/new effect during the recognition phase of the experiment, which has not been affected by mind-wandering and boredom instances during the encoding phase of the experiment. This novel finding corroborates the hypothesis that low-level visual processing may work independently of our conscious control, though more research is needed in this area. Consistent with previous research, our exploratory analyses showed the links between slower reaction times and increased levels of both mind-wandering and boredom during encoding, association between pupil size during encoding and accuracy during recognition and, interestingly, one novel finding was that state boredom was correlated with the number of blinks, which might be related to rising levels of fatigue with encoding task progression. Taken together, our findings contribute to the evidence that mind-wandering and boredom affect recognition memory differently and overall indicate different underlying mechanisms and levels of their attention depletion. Moreover, our findings support the reliability of the pupil old/new effect as a recognition memory measure and visual processing.

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Appendix

Demographic information questionnaire

Age

Please enter your age ________

Gender

o Female
o Male
o Other

Highest level of education

o Middle school degree
o High school degree (or equivalent)
o Bachelor's degree
o Master's degree
o Doctoral degree
o Other

Current occupation

o Full-time student
o Employed full-time (40+ hours a week)
o Employed part-time (less than 40 hours a week)
o Working and studying
o Unemployed (currently looking for a job)
o Unemployed (not looking for a job)

Prior to the memory test, did you think that your memory for the pictures might be tested?

o Yes
o Not sure
o No

If you answered "yes" or "not sure" to the previous question, did you try to intentionally memorize the pictures?

o Yes
o No

Experimental instructions

1. Welcome!

Today you are participating in an experiment about mind-wandering and boredom. The experiment is divided in two parts.

First part of the study

In the first part, that will last roughly 30 minutes, you will be presented with pictures, and you will be asked to determine if the item on the picture is man-made (created by humans) or natural. During the task you will be asked questions about mind-wandering. While looking at the screen, some people find their minds wandering away from the task. The shift of attention away from the external world to your internal thoughts is referred to as “mind-wandering”.

There are two main types of mind-wandering we are interested in:
1. Stimulus-dependent mind-wandering: Your thoughts will be related to the pictures and the task at hand.
2. Stimulus-independent mind-wandering: Your thoughts may wander to internal matters, such as memories from the past, future plans, or your current emotional state.

During the task, you will also be asked questions about boredom. Boredom is characterized by a desire to disengage from the current activity and engage in some other activity.

Press the space bar to continue.

2. Encoding instructions

In this part of the study, we ask you to look at some pictures on the screen. Please, fix your eyes on the fixation cross and use the keyboard without looking down. Several times during the experiment you will be interrupted with a question “How much are you mind-wandering right now?” with a scale ranging from 0% (completely on-task) to 100% (completely mind-wandering).

Please press the arrows on the keyboard to move the answer on the scale: left arrow for “on-task”, right arrow for “mind-wandering”. You can press "Shift" to move faster on the scale. If you notice that your attention was not concentrated on the task (answers from 50% - 100%), you will be able to indicate the type of mind-wandering you experienced: left arrow on the keyboard indicates “stimulus-dependent” mind-wandering, while the right arrow indicates “stimulus-independent” mind-wandering. The scales will appear on the screen, you don’t have to memorize it.

In addition to questions about mind-wandering, you will also be asked about boredom: “How bored are you right now?” on a scale ranging from 0% (not at all bored) to 100% (completely bored).

Before starting the actual experiment, you will be presented with four test trials, the mind-wandering and boredom questions to familiarize yourself with the procedure.

Press the space bar to continue with the test run.