How Much Do Our Eyes Give Away? Exploring the Effects of Mind Wandering on Pupil Size in a Near-Threshold Visual Detection Task

Elisabeta Chiriac

S4696875

Department of Psychology, University of Groningen

PS3E-BT: Bachelor's Thesis

Supervisor: Veera Ruuskanen

June 28th, 2024

Abstract

It is a well-known fact that the size of our pupils changes in response to external stimuli, such as light or the distance of an object to be perceived. In this sense, we know that our pupils dilate when looking at targets farther away or when exposed to light, whereas when we are in a dark environment or perceiving objects up close, our pupils constrict. However, internal factors such as cognitive or emotional arousal also play a role, as mental states seem to influence pupil size. One example is mind-wandering (MW), as defined by a decrease in task engagement, together with an increase in task-unrelated thoughts (TUTs). Using a near-threshold visual detection task across two lighting conditions, one in the dark and one in dim lighting, we aimed to explore the relationship between MW and pupil size, as measured during the detection task, which we hypothesized would be positively correlated. Additionally, we also explored the relationship between pupil size and task engagement (TE). Our analyses did not yield statistically significant results, suggesting that there might not be a strong link between either MW or TE, and pupil size. Possible theoretical explanations for this, as well as limitations of our study are further discussed.

Keywords: mind-wandering, pupil size, task engagement, pupillometry, visual perception, mental states

How Much Do Our Eyes Give Away? Exploring the Effects of Mind Wandering on Pupil Size in a Near-Threshold Visual Detection Task

Our mental states are by definition intrinsic, but oftentimes these can be reflected in our physiology, which is why our eyes have long been regarded as windows to the mind. Thus, our pupils can be very telling of our internal states, as well as mental or emotional arousal (Nakakoga et al., 2021). For example, when presented with emotionally strong images, either positive or negative, people often react more strongly compared to neutral images, which is reflected through pupil dilation (Bradley et al., 2008). Similarly, cognitive factors can also influence the size of our pupils, which Vilotijević and Mathôt (2023) argue might have functional benefits for visual perception.

Arousal Related Pupil Responses

Since internal processes such as emotions and cognition have been shown to influence pupil size, we can refer to them as arousal related responses (Bradley et al., 2008). There is an entire body of research so far suggesting that higher order cognitive processes influence the size of the pupil (Bradley et al., 2008; Groot et al., 2022; Nakakoga et al., 2021; Pelagatti et al., 2018; Unsworth & Robison, 2018), to which there seem to be certain functional benefits, by providing a form of sensory tuning (Vilotijević & Mathôt, 2023). In this sense, we know that larger pupil sizes reflect an increase in mental effort such as working memory, as a larger working memory load elicits a pupil dilation response (Unsworth & Robison, 2017). Additionally, Van Der Wel and Van Steenbergen (2018) suggest that it is not the inherent complexity of a task that determines the size of the pupil, but rather the subjective mental effort employed to deal with task demands.

The Nature of Mind-Wandering (MW) and Self-Generated Thoughts

Consequently, it would seem that mind-wandering (MW), as defined by low task engagement due to an external redirection of attention towards task-unrelated thoughts (TUTs), can also elicit a pupillary response. Pelagatti et al. (2018) found that pupil size can reflect levels of MW, as verbal cues that triggered MW, elicited pupil dilation. This finding provides further insight into the influence of cognitive factors on visual perception.

However, an important distinction to be made is between MW and mind-blanking (MB), the latter being defined by a low arousal state with decreased task engagement, however, lacking TUTs. These TUTs can be either self-generated, occuring for seemingly no reason, or triggered by external factors, thus often occurring unintentionally (Huijser, 2022), and sometimes with little to no conscious awareness of this mental state (Smallwood & Schooler, 2015). Moreover, it seems that MW occurs more often in contexts where there is no external demand for attention or cognitive effort, such as breaks, mundane tasks or dull environments (Huijser, 2022).

Context Regulation Hypothesis

Based on existing literature on MW, it seems that certain settings, such as ones that do not demand significant attention or cognitive effort, are more likely to elicit MW (Huijser, 2022; Smallwood & Schooler, 2015). With this in mind, Smallwood and Schooler (2015) elaborate on the Context Regulation Hypothesis, stating that favorable performance would limit self-generated mental content to instances where there is no significant external demand for attention. This falls in line with previous findings on the topic, considering that high levels of MW and TUTs in the context of a demanding task have been shown to hinder performance (Aston-Jones & Cohen, 2005).

Content Regulation Hypothesis

On top of the context in which MW can occur, the content of TUTs is also important, and has been shown to potentially vary in experimental settings, with autobiographical planning being one of the most frequent types of TUTs (Baird et al., 2011). Moreover, some research even suggests that the content or type of TUTs might be correlated with changes in our physiology, (Tulving, 2002; Smallwood & Schooler, 2015). Thus, according to Smallwood and Schooler (2015), the results of MW episodes, from a functional standpoint, depend on and can be reflected by the content and nature of the TUTs, including factors such as temporal focus or affective valence. Moreover, as TUTs vary in aspects such as type of memories retrieved, type of planning or meta-awareness of MW state, it is possible that physiological markers could offer more insight into the content of MW.

Types of Pupillary Responses to External Factors

The amount of light that enters the eye is determined by our pupils, which can either constrict or dilate in response to visual stimuli, and they do so through various mechanisms, one of them being the pupil light response (PLR). In a dark environment, our pupils dilate, while in bright environments, they constrict, in order to attune to the amount of available light (Mathôt & Van Der Stigchel, 2015). This happens because in conditions of decreased luminance, there is less visual information in the environment, and therefore, pupils dilate in order to allow more light in, increasing visual sensitivity as well. Similarly, when attending to a bright stimulus, the constriction of the pupil limits the amount of light entering the eye, which is then focused on the fovea, leading to high visual acuity (Vilotijević & Mathôt, 2023), and consequently, high discrimination performance. However, large pupils increase detection performance, at the expense of visual acuity, since optical blur increases (Eberhardt et al., 2022; Mathôt & Ivanov, 2019; Mathôt & Van Der Stigchel, 2015). Similarly, the pupil near response (PNR) offers insight into how the size of our pupils changes based on the distance of a perceived stimulus. Thus, when perceiving an object far away, our pupils dilate, whereas when looking at an object up close, they constrict (Mathôt, 2018).

The Biological Mechanism Behind Color Vision

The photoreceptors in our retina consist of rods, which are mainly used in scotopic, or night vision, and cones, which help us distinguish colors, and are thus useful in daylight, or photopic vision (Yantis & Abrams, 2017). While rods and cones are sensitive to different wavelengths of light, there are also several types of cones, each corresponding to different wavelengths, namely, short, medium, or long (Kalat, 2016). For example, in order to perceive the color blue, S-cones, which are sensitive to short wavelengths, are active, although when trying to perceive the color red, L-cones are activated, as they are sensitive to longer wavelengths. Similarly, rods also respond to shorter wavelengths, when brightness levels are low, and are sensitive at ~500 nm (Yantis & Abrams, 2017).

The Role of Locus Coeruleus (LC) Function on Pupil Size Changes

The locus coeruleus (LC) is a nucleus located in the brain stem, specifically in the pons, that plays a role in the release of norepinephrine in the brain (Gilzenrat et al., 2010), as well as regulating attentional processes by providing a balance between exploitation and exploration processes (Aston-Jones & Cohen, 2005). Thus, it seems that LC function could provide a neurological basis for explaining the link between pupil size and mental proceses.

Phasic and Tonic LC activity

Neurons in the LC seem to perform in either one of two ways when we observe their firing rate, namely, phasic or tonic (Aston-Jones & Cohen, 2005; Usher et al., 1999, as cited in Gilzenrat et al., 2010). In this sense, phasic LC activity is characterized by task-evoked firing, however with a lower rate of baseline firing in the LC, as well as better task performance, indicating a process of exploitation. Conversely, tonic LC activity is a better indicator of basline neural firing, characterized by a higher firing rate in the LC and reduced performance, thus favoring exploration over exploitation (Gilzenrat et al., 2010; Aston-Jones & Cohen, 2005; Usher et al., 1999). Moreover, tonic LC activity seems to be accompanied by an increase in pupil size, while the opposite is true for phasic LC activity (Gilzenrat et al., 2010). In the context of our study, this finding would imply that MW would be reflected by tonic activity in the LC, whereas disengagement from the task would correlate to phasic LC activity. Bearing this in mind, Aston-Jones and Cohen (2005) proposed the Adaptive Gain Theory, which builds on the two modes of LC activity, stating that perceived task utility is a mediating factor that balances the shift in LC activity from one mode to another. Therefore, according to this theory, any task with reduced perceived utility is more likely to elicit tonic firing in the LC, and thus, higher levels of MW (Aston-Jones & Cohen, 2005; Gilzenrat et al., 2010).

Present Study

Seeing as the size of our pupils is strongly mediated by internal processes, our study aims to answer the following question: Are levels of MW and task engagement reflected in pupil size changes in the context of a visual detection task?

In order to answer this, participants will engage in a near-threshold detection task while keeping their gaze fixated on a dot in the center of the screen. Additionally, the targets flashed on the screen during experimental trials consist of faint luminance patches of either red or blue color, as to excite different cone types, and the experiment includes two conditions, taking place either in the dark or in dim lighting. The targets are also flashed at different eccentricities on the screen, meaning that higher eccentricities would require bigger pupils for detection, as opposed to targets positioned closer to the center. Given that our question relates to internal processes, we aim to measure spontaneous fluctuations in pupil size, by recording pupil size right before stimulus presentation. In this sense, using a measurement of pupil size after stimulus presentation is what we would call a task-evoked pupil response, thus being determined by external experimental factors.

Therefore, we want to examine the relationship between MW and pupil size, as we assume that large pupil sizes will be positively correlated with high levels of MW, as well as low levels of task engagement.

Methods

Participants

Our sample consisted of 63 first year psychology students who took part in the experiment voluntarily, in exchange for partial course credits through the SONA participant recruitment platform at the University of Groningen. The requirement for participation included normal to corrected vision with either glasses or contact lenses, and normal color vision, and two participants completed the detection task while wearing glasses. On the basis of criteria developed by the EC-BSS at the University of Groningen, the study was exempt from full ethical review (PSY-2324-S-0311).

Materials

Questionnaires

Before proceeding with the detection task, participants completed two questionnaires of around five minutes each, the first one containing demographic information, and the second one being the MEQ (Horne & Ostberg, 1976). The type of demographic information that was collected included age, sex, number of hours slept the night before, handedness, and subjective level of sleepiness. Additionally, information about alcohol, caffeine and nicotine consumption within the last 24 hours was collected, in terms of number of units consumed.

Technical Specifications

The detection task, as well as baseline measurement, were coded in OpenSesame 4.0.13 (Mathot et al., 2012) using Python, and there was a GazePoint (Dondi et al., 2024) eye tracker used during the experiment, with a refresh rate of 60 Hz. Additionally, the monitor on which the experiment was conducted was a model PL2773H of the Iiyama's 27" Full-HD ProLite G2773HS, with screen size of 647 x 454.5 x 239 mm and resolution of 1920 x 1080 pixels per inch. The refresh rate of the computer was 120 Hz. Moreover, during the baseline measurement, the screen luminance was 4,83 cd/m2 and during the detection task, the luminance of the screen was 0,2 cd/m2. Moreover, at the highest opacity, the luminance of the red targets measured at 33,59 cd/m2, and the luminance of blue targets was 12,34 cd/m2. The opacity was adjusted during the experiment over multiple trials, for every participant. The illuminance in the room was 0 LUX in the dark condition during the detection task and baseline measurement, and in the light condition, illuminance was measured at 3 LUX during the detection task, and 6 LUX during the baseline measurement.

Detection Task

During the experiment, the measurement of the baseline pupil size was followed by the detection task, which involved fixating on a dot in the center of the screen, while targets flashed on the screen, upon which participants were instructed to press the spacebar. The monitor background during the task was black, and grey during the baseline measurement. The sequence of the task included one practice block containing 16 trials and during which the staircase was applied, three staircase blocks containing 56 trials each, and seven regular blocks, each containing 56 trials. The screen-by-screen sequence during a trial is also displayed in Figure 1.

Faint Luminance Patches

The targets consisted of faint luminance patches of either blue (#0000FF) or red (#FF0000) color, which were round shaped with a gaussian mask around the edges. The opacity of the targets was adjusted during the first 184 trials of the task using the staircase method, starting at 0.3 opacity for red targets, and 0.4 for blue targets. The difference in opacity for different colors is due to the fact that blue targets were harder to detect by comparison, and thus require higher opacity. The target onset time during a trial ranged from 1 and 2 seconds, the on-screen duration of the targets was 50 milliseconds, after which the trial lasted for another 1.5 seconds, making the total trial length from 2.5 to 3.5 seconds, as shown in Figure 1. The eccentricity of the targets ranged from 20 to 400 pixels, thus corresponding to a visual degree angle between 0.50 º and 2.47 º on the retina.

Staircase Procedure

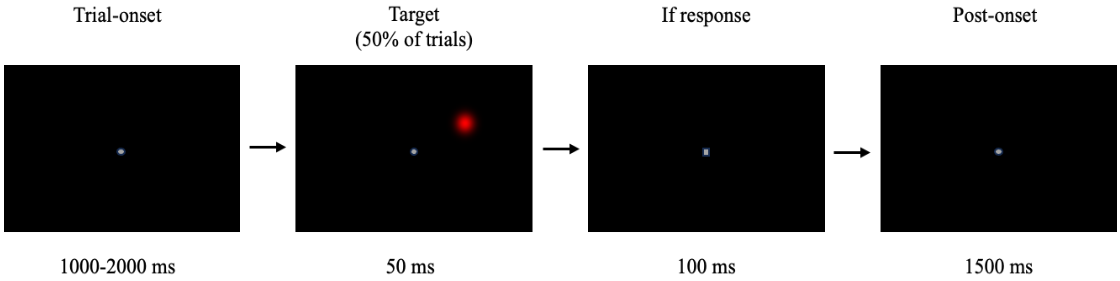
For the purpose of our near-threshold visual detection task, we used a staircase procedure in order to find the threshold of visual perception for each participant. The staircase trials in the detection task were coded as follows: blue (#0000FF) targets started at 0.4 opacity, while red (#FF0000) targets started from 0.3 opacity, 1 being the highest value, where the targets would be fully opaque. For each correct answer participants gave, opacity remained the same, although after three correct answers, the staircase increased by one step, thus decreasing opacity by a proportion of 0.1. However, for each wrong answer participants gave, the staircase decreased by one step, increasing opacity by 0.1 each time. The procedure consisted of three blocks, each containing 56 trials. Out of those, targets were only shown randomly in half of the trials; and half of the targets presented were red, while the remaining ones were blue.

Fixation Point

The fixation dot was presented at null eccentricity, in the center of the screen, with a size of 15 pixels in diameter. Moreover, during the task, the dot was programmed to briefly change to a square shape upon pressing the spacebar, in order to provide visual feedback, and maintained full opacity throughout the task, as highlighted in Figure 1.

Figure 1

Screen-by-Screen Sequence During One Trial of the Detection Task



Note. The figure shows an example of a trial where a red target is present at full opacity. During the experiment, the task included red and blue targets, for which opacity was adjusted.

MW Probes

The probes for MW were phrased as follows: “How much is your mind wandering right now?” with a Likert scale response option ranging from 1 - “not at all” to 7 - “very much” and “How focused on the task are you right now?” with a Likert scale response option ranging from 1 - “not at all focused” to 7 - “very focused”. The frequency of thought probes was chosen to be shown six times per session for each participant, and the trials in which the MW probes were chosen to appear was pseudorandomized. For each participant, the trial was chosen randomly out of seven generated lists with gaps in between, in such way that probes would not appear one right after another, nor in the first trials of the detection task. The interval for MW was chosen so that they could appear at least after trial 90. Only trials where MW probes were shown were used in the analysis, as delineated by the change of participants' ratings on the questions. Despite there being seven generated lists, the majority of participants completed the task in such way that the probes were only shown six times. Furthermore, only four out of six trials on which the probes were shown were included per participant in the final analysis, since trials were only included if the probe ratings changed, but not if they remained the same as in previous trials.

Procedure

Participants signed up voluntarily through a web-based participant recruitment platform at the University of Groningen, in exchange for partial course credits. Upon arrival, they were offered information about the research and asked to provide informed consent before proceeding with the questionnaires. The study was conducted using a within-participants design and participants completed a visual detection task in both conditions, either light or dark, each to be completed in a separate session. The order of conditions was counterbalanced for both sessions across participants, and both sessions could not be scheduled more than seven days apart from one another. The dark sessions took place with the lights off, at 0 LUX illuminance in the room, while the light sessions took place in a dimly lit room, at the lowest possible level, which measured at 3 LUX during the detection task. In case of a dark session, only the demographics questionnaire was completed, while in the light session they were both administered.

Before proceeding to calibrate the GazePoint eye tracker, participants placed their head on a chin rest, which was adjusted in such way that they could keep still for the duration of the task, followed by a measurement of their baseline pupil size over the course of five minutes, which took place in the same lighting conditions as the detection task, for each condition. After explaining the task, people in the dark session were asked to undergo a dark adaptation procedure before starting the detection task, which ranged from eight to ten minutes.

Analysis

The preprocessing of the data was done using the GazePoint parser module, included in the python package eyelink parser. The default trace processor was used, and blinks in the pupil measurement data were removed, rather than interpolated. The data was cropped to one second before stimulus presentation, from which the average pupil size value per trial was then extracted.

Furthermore, in order to explore the relationship between MW and pupil size, a correlation was computed for each participant across conditions between pupil size and task engagement, as well as pupil size and MW, for which the resulting sample of correlations was tested against 0 using a one sample t-test. Additionally, we used a Linear Mixed Model to test for main effects of MW, task engagement and lighting condition on pupil size, as well as interactions between predictors.

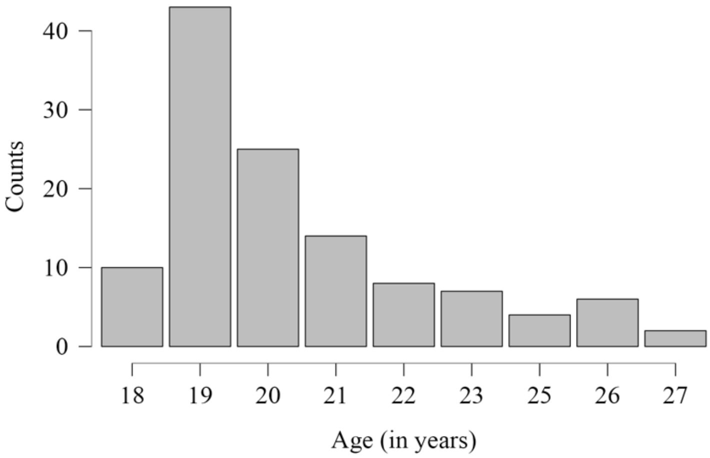
Results

Descriptive statistics

Our sample consisted of 63 participants, with $M_{age} = 20.4$ and $SD_{age} = 2.05$. The age distribution of our sample was right-skewed, as can be seen in Figure 2.

Figure 2

Histogram showing Age Distribution of Participants



In the light condition, the distribution of average pupil measurements is depicted in Figure 3, and the distribution of average pupil size in the dark condition is displayed in Figure 4. Over the trials during which the probes were shown, mean pupil size in the light condition was M = 25.98, SD = 5.99, while in the dark condition M = 24.05, SD = 4.25

Figure 3

Boxplot Depicting Average Pupil Sizes in the Light Condition

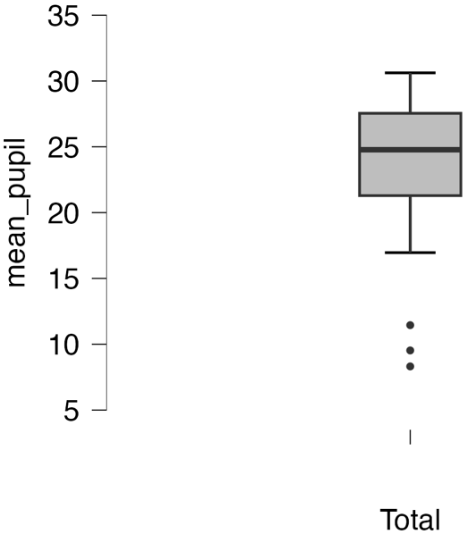
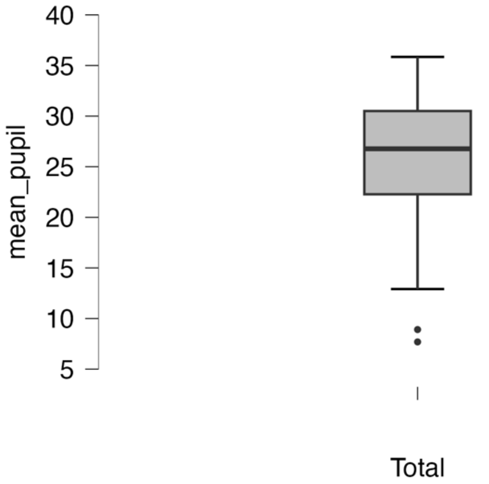


Figure 4

Boxplot Depicting Average Pupil Sizes in the Dark Condition



Our variables of interest for pupil size consist of MW and focus level, which, after computing a Pearson's r correlation coefficient, seem to be moderately negatively correlated, with r = - 0.66, and p = 0.00, indicating a measure of dependent constructs.

Main Analysis

Our main analysis pertains to the effects that MW and task engagement, as well as lighting conditions have on pupil size. In this sense, we chose to explore this using Linear Mixed Modeling, for which we fitted two models: in the first model, we used MW, task engagement and lighting conditions as independent variables, while including main effects and interactions of the predictors, as well as random intercepts, whereas the second model also included random slopes for each predictor. The first model revealed an AIC = 624.84, while the second revealed an AIC = 674.20. This indicates a better fit of the first model, compared to our second one, which is why we further used it in our analysis.

Our model revealed no significant main effects, with p > 0.05 for both MW and task engagement. Similarly, lighting conditions do not seem to have significant effects on pupil size, with $p > 0.05$. A possible reason for this is the small difference in illuminance between our experimental conditions, as they either take place in the dark or in dim lighting. Additionally, it seems that there are no significant interactions between any of our predictors ($p > 0.05$).

Correlational Analysis

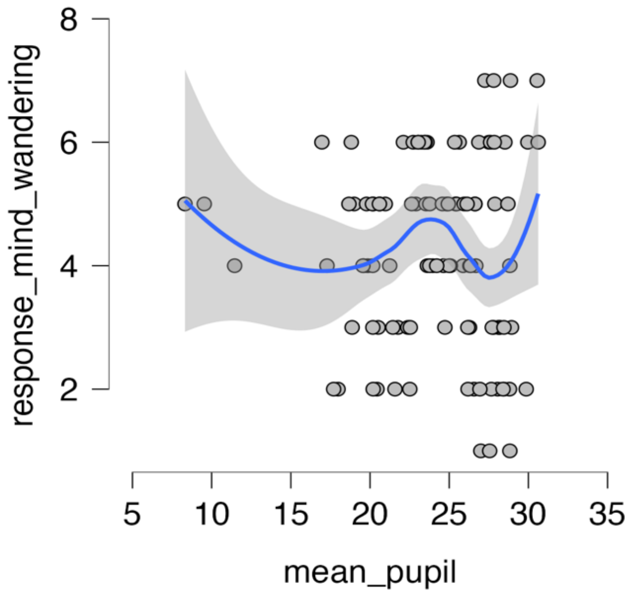
The aim of our study is to explore the relationship between MW and pupil size, as seen through levels of MW and task engagement. In order to do this, the correlation between MW and pupil size, as well as task engagement and pupil size was computed for each participant, for both the light and dark condition. The sample of correlations was further tested using a one sample t-test to determine whether they were, on average, significantly different from 0. For this analysis, data from 44 participants was used in the dark condition, while in the light condition the analysis included data from 37 participants.

Dark Condition

In the dark condition, the average correlation between MW and pupil size was $M=0.128$, $SD = 0.632$, and the average correlation between task engagement and pupil size was $M = 0.088$, $SD=0.594$. Furthermore, due to the normality assumption being violated, as revealed by a Shapiro-Wilk test with $p = 0.003$ for MW and $p = 0.011$ for task engagement, a Wilcoxon Signed Rank Test was used, which revealed a rank-biserial correlation = 0.240 with $p = 0.168$ for MW, and a rank-biserial correlation = 0.176 for TE with $p = 0.327$, revealing non-significant results.

Figure 5

Scatterplot of MW Ratings Across Pupil Sizes in the Dark Condition



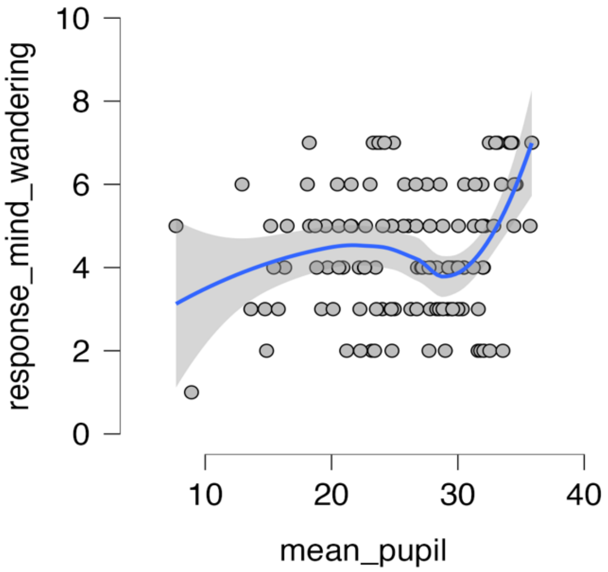
Light Condition

In the light condition, the average correlation coefficient of MW and pupil size was M= 0.186, SD = 0.628, and the average correlation of task engagement and pupil size was M = -0.028, SD=0.656.

Furthermore, the same procedure was used similarly to the dark condition. For MW, the Shapiro-Wilk test revealed p=0.004 for MW, and p=0.008 for task engagement, indicating a violation from normality, once again. Thus, a Wilcoxon Signed Rank Test was used and revealed no significant results, with p = 0.107 for MW, respectively p = 0.893 for TE.

Figure 6

Scatterplot of MW Ratings Across Pupil Sizes in the Light Condition



Discussion

The aim of this study focuses on exploring the relationship between pupil size and MW, as defined by low task engagement and a high number of TUTs. In order to do this, we asked participants to rate their levels of MW and task engagement during a visual detection task, which we then correlated with their average pupil size during those trials in which the questions were asked. Our results did not prove to be statistically significant, suggesting that there is no correlation between pupil size and MW. Although our research does not offer much insight into causal factors, it seems that the two are not related.

Possible Explanations

As previously mentioned, some existing research suggests a possible link between MW and pupil size (Pelagatti et al., 2018), although this is still a debated topic. Moreover, due to the internal nature of MW, this topic requires novel methodology, making it harder to research without proper tools.

Methodology

In the context of our study, an important detail to point out is that the visual detection task itself is not particularly engaging for the participants and can be quite dull, which leads to a few possible explanations. One possibility is that this could lead to participant fatigue, implying not only the possibility of unreliable responses, but also a lack of variation within the probe data regarding mental states. Additionally, it could also likely be the case that a good enough distinction was not made between MW and MB. Therefore, although our thought probes were related to both MW and task engagement, no other measures were used in this sense. What is more, in the event that one’s mind is wandering to the extent that it affects task performance, it is safe to say that such conceptual distinctions could easily be missed on thought probes during quick-paced trials.

Theoretical discussion

If we reflect on the current methodology through the lens of the Context Regulation Theory (Smallwood & Schooler, 2015), this would suggest that the nature of our detection task would elicit MW, as well as a high number of TUTs, since the experimental setup allowed for breaks and included a monotonous task. Therefore, if we account for any additional factors, provided that MW was indeed high during the task, the Content Regulation Theory (Smallwood & Schooler, 2015) would imply that the type of TUTs could elicit different physiological responses, and thus, different pupil sizes. In this sense, we could also hypothesize that the mental content generated during the task was not emotionally arousing or salient, being of neutral valence. Moreover, this also highlights the fact that our methodology did not explore the content of MW episodes and types of TUTs, making this an important implication for future research.

In addition to this, if we consider the Adaptive Gain Theory (Aston-Jones & Cohen, 2005), we can argue that perceived task utility could be a potential confound. Therefore, it is possible that due to differences in perceived task utility across participants, which could result from distinctions in the perceived demand characteristics of the experiment, exploitation processes could have been favored at the expense of exploration. However, without adequate measurement of LC function, this only allows us to speculate.

Limitations and Directions for Future Research

A main limitation of this study includes the fact that eye tracking was the only physiological measure recorded, leading to a lack of control variables. However, a promising topic for future research consists of LC function and its influence on pupil size, as this could offer more insight into the neurological mechanisms behind TUTs. Additionally, our small sample of computed correlations could be a limitation, given that multiple exclusion criteria were used when parsing the data.

Although there has been increasing interest on the topic of MW, plenty of research is still needed in order to better understand the mechanisms behind it. Therefore, some possible developments include using auditory or visual cues in order to trigger TUTs, as well as exploring the content of MW in combination with physiological measurements. Another important consideration consists of the effect of perceived task utility on performance. Lastly, we believe that exploring MW independently from MB could offer valuable insight on the effects of TUTs and task engagement on pupil size.

References

Alnaes, D., Sneve, M. H., Espeseth, T., Endestad, T., Van De Pavert, S. H. P., & Laeng, B. (2014). Pupil size signals mental effort deployed during multiple object tracking and predicts brain activity in the dorsal attention network and the locus coeruleus. *Journal of Vision*, *14*(4), 1–1. https://doi.org/10.1167/14.4.1

Aston-Jones, G., & Cohen, J. D. (2005). AN INTEGRATIVE THEORY OF LOCUS COERULEUS-NOREPINEPHRINE FUNCTION: Adaptive Gain and Optimal Performance. *Annual Review of Neuroscience*, *28*(1), 403–450. https://doi.org/10.1146/annurev.neuro.28.061604.135709

Baird, B., Smallwood, J., & Schooler, J. W. (2011). Back to the future: Autobiographical planning and the functionality of mind-wandering. *Consciousness and cognition*, *20*(4), 1604-1611.

Bradley, M. M., Miccoli, L., Escrig, M. A., & Lang, P. J. (2008). The pupil as a measure of emotional arousal and autonomic activation. *Psychophysiology*, *45*(4), 602–607. https://doi.org/10.1111/j.1469-8986.2008.00654.x

Brocher, A., Harbecke, R., Graf, T., Memmert, D., & Hüttermann, S. (2018). Using task effort and pupil size to track covert shifts of visual attention independently of a pupillary light reflex. *Behavior Research Methods*, *50*(6), 2551–2567. https://doi.org/10.3758/s13428-018-1033-8

Costa, V. D., & Rudebeck, P. H. (2016). More than Meets the Eye: The Relationship between Pupil Size and Locus Coeruleus Activity. *Neuron*, *89*(1), 8–10. https://doi.org/10.1016/j.neuron.2015.12.031

Dondi, P., Sapuppo, S., & Porta, M. (2024). Leyenes: A gaze-based text entry method using linear smooth pursuit and target speed. *International Journal of Human-Computer Studies*, *184*, 103204. https://doi.org/10.1016/j.ijhcs.2023.103204

Eberhardt, L. V., Strauch, C., Hartmann, T. S., & Huckauf, A. (2022). Increasing pupil size is associated with improved detection performance in the periphery. *Attention, Perception, & Psychophysics*, *84*(1), 138–149. https://doi.org/10.3758/s13414-021-02388-w

Franke, K., Willeke, K. F., Ponder, K., Galdamez, M., Zhou, N., Muhammad, T., Patel, S., Froudarakis, E., Reimer, J., Sinz, F. H., & Tolias, A. S. (2022). State-dependent pupil dilation rapidly shifts visual feature selectivity. *Nature*, *610*(7930), 128–134. https://doi.org/10.1038/s41586-022-05270-3

Gabay, S., Pertzov, Y., & Henik, A. (2011). Orienting of attention, pupil size, and the norepinephrine system. *Attention, Perception, & Psychophysics*, *73*(1), 123–129. https://doi.org/10.3758/s13414-010-0015-4

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

Groot, J. M., Csifcsák, G., Wientjes, S., Forstmann, B. U., & Mittner, M. (2022). Catching wandering minds with tapping fingers: Neural and behavioral insights into task-unrelated cognition. *Cerebral Cortex*, *32*(20), 4447–4463. https://doi.org/10.1093/cercor/bhab494

Hood, A. V. B., Hart, K. M., Marchak, F. M., & Hutchison, K. A. (2022). Patience is a virtue: Individual differences in cue-evoked pupil responses under temporal certainty. *Attention, Perception, & Psychophysics*, *84*(4), 1286–1303. https://doi.org/10.3758/s13414-022-02482-7

Horne, J. A., & Ostberg, O. (1976). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *International journal of chronobiology*, *4*(2), 97–110.

Huijser, S. (2022). *The Wandering Mind: Investigating what drives self-generated thinking and determines its adaptive or maladaptive consequences* [University of Groningen]. https://doi.org/10.33612/diss.198707305

Kalat, J. W. (2006). *Biological psychology*. SAGE.

Konishi, M., Brown, K., Battaglini, L., & Smallwood, J. (2017). When attention wanders: Pupillometric signatures of fluctuations in external attention. *Cognition*, *168*, 16–26. https://doi.org/10.1016/j.cognition.2017.06.006

Mathôt, S. (2018). Pupillometry: Psychology, Physiology, and Function. *Journal of Cognition*, *1*(1), 16. https://doi.org/10.5334/joc.18

Mathôt, S., & Ivanov, Y. (2019). The effect of pupil size and peripheral brightness on detection and discrimination performance. *PeerJ*, *7*, e8220. https://doi.org/10.7717/peerj.8220

Mathôt, S., & Van Der Stigchel, S. (2015). New Light on the Mind's Eye: The Pupillary Light Response as Active Vision. *Current Directions in Psychological Science*, *24*(5), 374–378. https://doi.org/10.1177/0963721415593725

Mathôt, S., Berberyan, H., Büchel, P., Ruuskanen, V., Vilotijević, A., & Kruijne, W. (2023). Effects of pupil size as manipulated through ipRGC activation on visual processing. *NeuroImage*, *283*, 120420. https://doi.org/10.1016/j.neuroimage.2023.120420

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324. https://doi.org/10.3758/s13428-011-0168-7

Mathôt, S., Van Der Linden, L., Grainger, J., & Vitu, F. (2013). The Pupillary Light Response Reveals the Focus of Covert Visual Attention. *PLoS ONE*, *8*(10), e78168. https://doi.org/10.1371/journal.pone.0078168

Mohanty, A., Gitelman, D. R., Small, D. M., & Mesulam, M. M. (2008). The spatial attention network interacts with limbic and monoaminergic systems to modulate motivation-induced attention shifts. *Cerebral cortex (New York, N.Y. : 1991)*, *18*(11), 2604–2613. https://doi.org/10.1093/cercor/bhn021

Nakakoga, S., Shimizu, K., Muramatsu, J., Kitagawa, T., Nakauchi, S., & Minami, T. (2021). Pupillary response reflects attentional modulation to sound after emotional arousal. *Scientific Reports*, *11*(1), 17264. https://doi.org/10.1038/s41598-021-96643-7

Pelagatti, C., Binda, P., & Vannucci, M. (2018). Tracking the Dynamics of Mind Wandering: Insights from Pupillometry. *Journal of Cognition*, *1*(1), 38. https://doi.org/10.5334/joc.41

Robison, M. K., Diede, N. T., Nicosia, J., Ball, B. H., & Bugg, J. M. (2022). A multimodal analysis of sustained attention in younger and older adults. *Psychology and Aging*, *37*(3), 307–325. https://doi.org/10.1037/pag0000687

Smallwood, J., & Schooler, J. W. (2015). The Science of Mind Wandering: Empirically Navigating the Stream of Consciousness. *Annual Review of Psychology*, *66*(1), 487–518. https://doi.org/10.1146/annurev-psych-010814-015331

Tulving, E. (2002). Episodic memory: From mind to brain. *Annual review of psychology*, *53*(1), 1-25.

Unsworth, N., & Robison, M. K. (2017). The importance of arousal for variation in working memory capacity and attention control: A latent variable pupillometry study. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(12), 1962–1987. https://doi.org/10.1037/xlm0000421

Unsworth, N., & Robison, M. K. (2018). Tracking arousal state and mind wandering with pupillometry. *Cognitive, Affective, & Behavioral Neuroscience*, *18*(4), 638–664. https://doi.org/10.3758/s13415-018-0594-4

Usher, M., Cohen, J. D., Servan-Schreiber, D., Rajkowski, J., & Aston-Jones, G. (1999). The role of locus coeruleus in the regulation of cognitive performance. *Science*, *283*(5401), 549-554.

Van Der Wel, P., & Van Steenbergen, H. (2018). Pupil dilation as an index of effort in cognitive control tasks: A review. *Psychonomic Bulletin & Review*, *25*(6), 2005–2015. https://doi.org/10.3758/s13423-018-1432-y

Vilotijević, A., & Mathôt, S. (2023a). Emphasis on peripheral vision is accompanied by pupil dilation. *Psychonomic Bulletin & Review*, *30*(5), 1848–1856. https://doi.org/10.3758/s13423-023-02283-5

Vilotijević, A., & Mathôt, S. (2023b). Functional benefits of cognitively driven pupil-size changes. *WIREs Cognitive Science*, e1672. https://doi.org/10.1002/wcs.1672

Wang, C.-A., & Munoz, D. P. (2015). A circuit for pupil orienting responses: Implications for cognitive modulation of pupil size. *Current Opinion in Neurobiology*, *33*, 134–140. https://doi.org/10.1016/j.conb.2015.03.018

Wang, C., & Munoz, D. P. (2021). Differentiating global luminance, arousal and cognitive signals on pupil size and microsaccades. *European Journal of Neuroscience*, *54*(10), 7560–7574. https://doi.org/10.1111/ejn.15508

Yantis, S., & Abrams, R. A. (2017). *Sensation and perception* (Second edition). macmillan education.