Influence of Pupil Size on Visual Detection Performance under External Visual Noise Conditions

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Abstract

This study explored the effect of pupil size on visual detection performance at different levels of external noise. Participants completed a visual detection task modified with 1/f noise. Pupil size was measured and data were analyzed using RM-ANOVAs. Visual detection performance decreased significantly as noise level increased for both small and large pupil sizes. Larger pupil sizes were associated with a significantly better performance compared to smaller pupil sizes. No interaction effect was found between pupil size and noise level. Finally, no significant effects in performance over time in a block of trials were found. This study provides a novel approach on visual detection and sensitivity by incorporating external visual noise for the first time. The findings reinforce that large pupils are associated with better visual sensitivity. Practical implications include improving task designs and executions where visual detection is critical, such as aviation. Future research should explore the neurocognitive mechanisms underlying these effects, further investigate the absence of an interaction effect, and look for adjusted ways to analyze performance over time.

Keywords: Pupil size, Visual Detection Task, External Visual Noise

Influence of Pupil Size on Visual Detection Performance under External Visual Noise Conditions

The gate of the soul, the eye's window or even a tiny universe are all figurative descriptions of our pupils. While captivating, these descriptions can hint at the complex and lesser understood mechanisms of pupil functioning. Pupillometry started as early as the 19th century with standout fundamental research being done by for example Kahneman and Beatty (1966). Their work explored cognitive load affecting pupil size, showing that pupil size could reflect cognitive processes and not just emotional states. Research has been ongoing ever since as fundamental findings, relationships and interactions are still there to be found. This research aims to add another dimension to this growing body of work.

The pupils regulate how much light enters the eye by changing their size. This process is known as the pupil light reflex (PLR) (Campbell & Gregory, 1960). In short, when light is in abundance the pupil contracts, improving visual acuity, and when light is scarce the pupil dilates resulting in more light entering the eye, thus improving visual sensitivity. Rods and cones are the primary photoreceptors of the retina, where rods are responsible for vision at low luminance and cones for vision at high luminance (Zele & Cao, 2015). However, Berson et al. (2002) found a third photoreceptor was also present namely the intrinsically photosensitive ganglion cells (ipRGCs). The ipRGCs modulate pupil size through light associated with circadian circumstances, in particular, blue light which causes a sustained constriction of the pupil. All three types of photoreceptors drive the PLR, each responding to different light conditions to regulate pupil size.

The PLR is seen as a bottom-up process, however Vilotijević and Mathôt (2023) argue that the top-down process of so-called *cognitively driven pupil-size changes* can modulate these pupil size changes. The authors argue that this would be a form of sensory tuning: a subtle optimization of visual-information intake that is tailored to the demands of the current situation and the immediate future. Attention, working memory, mental imagery, subjective perception and semantics have all been shown to affect pupil size (as reviewed in Vilotijevic & Mathôt, 2023). Pupil size tends to increase when tasks get harder across different cognitive domains (Van der Wel & Steenbergen, 2018; Wang et al., 2018). Cognitively driven pupil-size changes are also dependent on contextual factors. Variables such as the color, the target being in the central or peripheral vision, the lens quality and the visual task all determine the optimal pupil size (Franke et al., 2022; Aspinall et al., 2014; Winn et al., 1994; Mathôt & Ivanov, 2019).

The neurocircuitry of pupil size control consists of multiple systems. Pupil size control is mainly attributed to noradrenergic activity stemming from the locus coeruleus (LC). However, other areas like the dorsal raphe serotonin system, the acetylcholine system or the more recently explored orexin/hypocretinergic system of the lateral hypothalamus have increasingly been found to affect pupil size (Grujic et al., 2024). Given these recent insights it has been clear that pupil size readouts have been more context-dependent than previously thought. For instance, Megemont et al. (2022) argue that pupil-LC coupling is brain state dependent and states such as high motivation/engagement could result in a stronger coupling. There is great importance in generating and analyzing pupil size data for understanding brain function and design, which could lead to improvements in pupil-size diagnostics for neurological disorders.

Recent EEG research examined the relationship between pupil size and arousal. Ruuskanen et al. (2024) found that larger pupil sizes are associated with improved detection of near-threshold stimuli. The study revealed positive correlations between pupil size and power in the alpha and beta bands, which are respectively associated with cortical excitability and motor activity. Additionally, there was a specific association with suppression of the theta band and improved detection sensitivity. Crucially, these were independent effects: the effect of pupil size on detection sensitivity was not driven by cortical excitability. This suggests that theta band suppression improves visual detection through different neural mechanisms and pupil size could improve visual detection through optical effects or arousal, or both.

Visual detection tasks have been widely used in pupillometry. Visual detection tasks measure the detection of faint stimuli without requiring identification of their specific features (Vilotijević & Mathôt, 2023). Participants focus on a centered dot on a screen and at different intervals a target may appear in their peripheral vision. After a certain period, the participants will be instructed to answer if they noticed a target or not. Smaller pupils are associated with improved discrimination of fine stimuli in central vision while large pupils are associated with improved detection of faint stimuli in peripheral vision (Mathôt & Ivanov, 2019; Eberhardt et al., 2021). Mathôt (2020) argues that a large pupil allows more light into the eye, which increases the signal, therefore improving detection of near-threshold stimuli. No studies have yet explored how external visual noise affects performance in visual detection tasks while tracking pupil size changes. This is the focus of the present research.

The signal-to-noise ratio (SNR), among other kinds of signal processing situations, measures the clarity of a perception of vision. The clearer an image the higher the SNR and the more trouble one has with discerning the image the lower the SNR. Noise can be either internal noise or external noise. Internal noise refers to the inherent variability in neural processing and can be classified into three types: early noise, photon noise and late noise (Silvestre et al., 2018).

In the context of this study, external noise is seen as either auditory noise or visual noise. External visual noise refers to interfering visual information which is not related to the targeted signal and originates from outside the internal visual system. While this study focuses on visual noise, a small study showed that as auditory noise gets louder, the pupil size also increases (Antikainen & Niemi, 1983). The increase in pupil size is however limited to the initial hearing of the sound, whereafter it is suggested habituation takes place and pupil sizes constrict to normal levels. The current study aims to explore if these findings are also applicable to varying external visual 1/f noise levels and its effect on near-threshold detection performance.

By incorporating external noise, such as increasing the difficulty of spotting faint stimuli, the effect of internal noise can be quantified (Pelli & Farrell, 1999). This allows for a better understanding of visual processing and the role of internal noise. It enables the testing of contrast sensitivity limits by systematically increasing external noise and analyzing the point at which external noise becomes dominant over internal noise. The study by Silvestre et al. (2018) shows that the variation in contrast sensitivity (the ability to distinguish object from the background) can be explained through the three types of internal noise mentioned earlier. The three types are dominant at different levels of luminance and spatial frequency. Early noise occurs early in the visual processing pathway and will most likely be the significant factor for performance in this task as it dominates at low luminance and low spatial frequencies, thus when the stimulus is dim and coarse. The study kept pupil size constant in quantifying the different internal noise sources, thus the question remains what role pupil size plays in determining the effect of noise on performance. Therefore, the current study aims to better understand the mechanisms by which pupil size affects visual detection while external visual levels of noise are present.

To summarize, this study focuses on visual detection performance at different levels of external visual noise while tracking pupil size changes. 1/f Noise (pink noise) was used, because it was decided that 1/f noise came across as more naturally occurring visual external noise and is thought that it better mimics the internal noise present in the system, as opposed to white noise. In-trial pre-stimulus pupil size measurements will be the focus of this within-subjects research.

With increasing levels of noise, I hypothesize that visual detection performance will be worse as the distinction between the noise and target will become more difficult to spot. I will also explore a potential interaction between pupil size and noise level, but I refrain from hypothesizing the direction or nature of this interaction. Secondly, I hypothesize that when participants have a bigger pre-stimulus pupil size, performance is better compared to when the participants perform the task while having smaller pre-stimulus pupil sizes in a separate trial. Lastly, I hypothesize that as the task exists of blocks with break in between, performance for all participants will be higher at the beginning of each block and reduce over time until the break, whereafter performance will be improved again. This hypothesis would align with the observations of the auditory noise experiment (Antikainen & Niemi, 1983) where pupil sizes habituated to the exposure of the noise and constricted to baseline size over time. If pupil size constricts over time, I expect that performance will decrease, as outlined in hypothesis 2.

Participants were also asked to complete self-reports on several explanatory variables like ADHD symptoms, emotions, arousal, motivation and reward processing. This study focuses solely on the dynamics of visual detection performance with visual noise and pupil sizes and will not explore the other variables.

Methodology

Participants

57 participants (40 females, 17 males, M_{age} = 19.6, SD_{age} = 1.84) took part in this study. All participants had normal or corrected vision by using contact lenses. Participants were recruited through Sona Systems of the University of Groningen. Therefore, it should be mentioned that all participants are psychology students. No power analysis was performed to determine sample size, however this sample size is twice the size of other comparable studies, which leads to the belief that there is sufficient power.

The experiment was approved by the ethics committee of the psychology department at the University of Groningen (study code: PSY-2425-S-0055). All participants provided written consent and obtained Sona points for their participation which are mandatory for their degree.

Participants completed a questionnaire before taking the visual detection task. The goal of the questionnaire was to gain insight into demographic data and the exploratory variables. The emotion variable was assessed with the Self Assessment Manikin (Bradley & Lang, 1994). The ADHD variable was assessed with Adult ADHD Self-Report Scale (Kessler et al., 2005). The attention variable was assessed with the Attention Control Scale (Townschend & Bornschlegl, 2024) and motivation and reward questions were created by the other collaborators themselves. These variables were measured with Likert scale, frequency scale or rating scale questions. The exploratory variables were not analyzed for this study but were used by other collaborators in this research project.

Visual Detection Task

Participants completed a near-threshold visual detection task consisting of reporting the presence of a faint peripherally presented stimulus while varying levels of external visual noise were present on the screen. The experiment and stimuli were created with and controlled by OpenSesame (version 4.0.24, Melodramatic Milgram) (Mathôt et al., 2012).

The stimulus was presented on a grey (RGB = 128, 128, 128) background with a luminance of 14.8 cd/m^2 while varying levels of external visual 1/f noise were present. The possible levels of 1/f noise were continuous between the opacity values 0.1 and 0.6 and were randomly determined at each trial (Figure 1). The luminance of noise ranged between 16.82 and 18.12 cd/m^2. A circular grey fixation dot (RGB = 89, 89, 89) with a size of 0.44° of visual angle (20 px) was maintained in the center of the screen throughout the experiment (Figure 1).

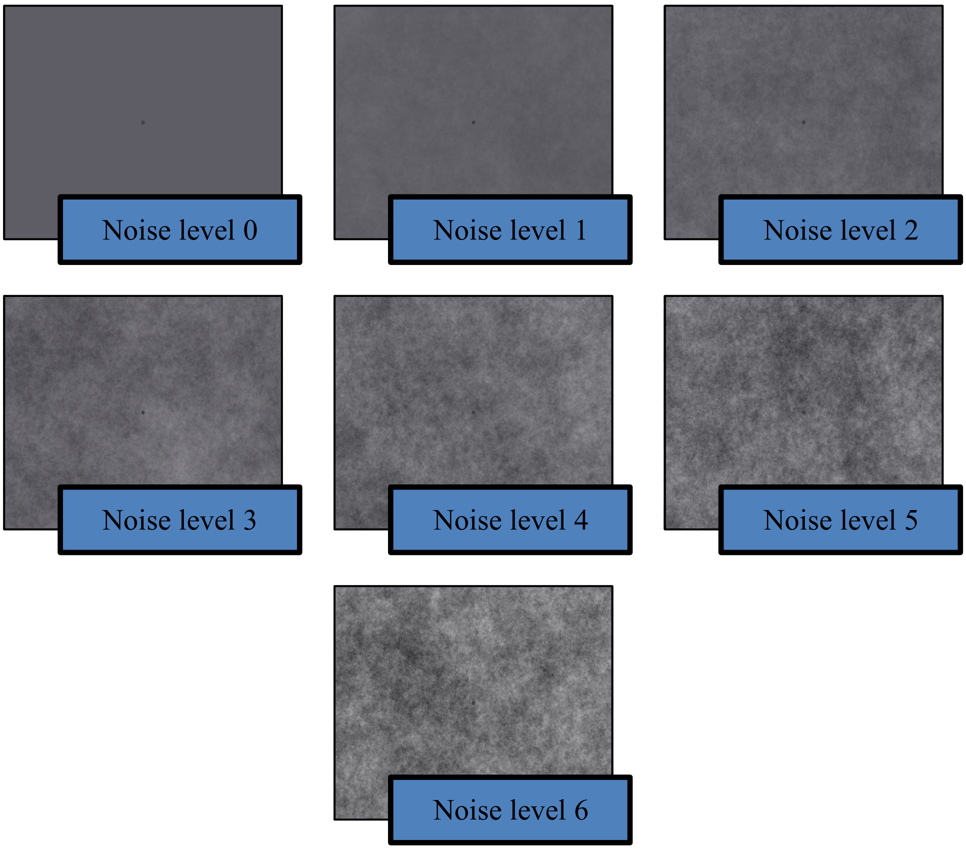


Figure 1: External visual 1/f noise levels.

The to-be-detected target stimulus was a white luminance patch (RGB = 255, 255, 255) with a Gaussian envelope with a standard deviation of 0.65° (30 px) (figure 2). The luminance of the stimulus at full contrast was 111.64 cd/m^2, however actual luminance during the task would be significantly lower. A Quest adaptive staircase procedure to keep overall accuracy fixed at 75% was implemented at the practice trials and first experimental block, with noise level constant at 0.3, which adjusted the contrast of the stimulus. This procedure resulted in the stimulus-luminance during the task being lower. A random angle between 0° and 360° was drawn to determine the stimulus location with a fixed eccentricity of 8.72° of visual angle (400px).

The total trial length was between 4-5 seconds and the target appeared between 50ms after the start of the trial and 50ms before the end of the trial. On half of the trials the target stimulus was present and flashed for 50 milliseconds. After 4-5 seconds had passed a new slide appeared with only a question mark indicating that the participant must make a choice. Choices were made by either pressing the left arrow on the keyboard to answer that they had not seen the target stimulus or pressing the right arrow on the keyboard to answer that they had seen the target stimulus. After giving their answer, participants automatically continued to the next trial.

At pseudo-random times during the task a slide would show with a rating scale question from 1-5 asking the participant to rate their current motivation, which was completed by using the mouse. The motivation question could only be asked once per block and blocks 1 and 2 were excluded, resulting in 8 times where the participant was asked to answer the question. Participants had received instructions before starting the experimental phase that a motivation related question could be presented. The motivation questions were presented for another research project.

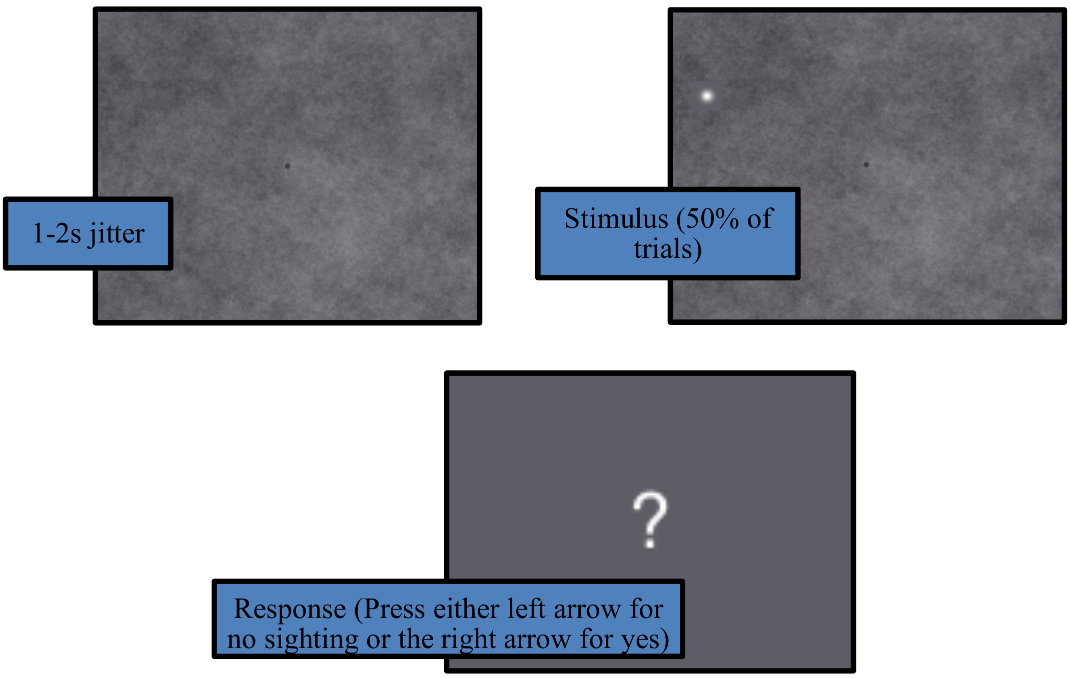


Figure 2: Visual Detection Task. Illustration is not to scale. Stimulus contrast is lower than in the actual experiment. A medium noise level was used for illustration purposes.

Before the experimental phase started, a practice phase was administered. The practice phase consisted of 10 trials (1 Block) as the task was not considered to be hard to understand and thorough practice was not considered necessary. The experimental phase had 400 trials, and the trials of this phase were divided into 10 blocks, separated by self-paced breaks. Practice and staircase trials were not used in the analysis, thus the analysis uses 360 trials per participant. Participants did not receive feedback on their performance during the task.

The experiment was presented on a 27-inch (68 cm) Iiyama Prolite (model number: G2773HS) running at a refresh rate of 120 Hz and 1920 x 1080 resolution. The viewing distance was approximately 60 cm for all participants.

Pupil size measurement

A Eyelink 1000 eye tracker (SR Research Ltd., 2022) with a 35 mm lens was used to measure pupil size of the right eye. A 5-point calibration procedure was performed at the beginning of the experiment consisting of looking at a stimulus at different points on the monitor. Afterwards a validation procedure was conducted to assure accuracy. A 2-minute baseline measure was then administered by looking at the grey fixation dot. Pupil size was measured continuously throughout each trial but stopped when participants had a break between blocks. Participants rested their head on a chinrest throughout the experiment, keeping the distance to the eye tracker fixed at 60 cm. The illuminance at the chinrest was 6 LUX.

Procedure

Arriving in the lab, participants received verbal and written information and gave written consent to partake in the study. Next, participants first finished a questionnaire for demographic data and various unused explanatory variables (mentioned in the introduction & methods) using Qualtrics. Afterwards the eye tracker was calibrated and a baseline measurement was administered.

Following this, participants completed the visual detection task. Again, the participants received instructions for the task, this time on screen and participants were asked if they had any questions. The light-source in the room was constant for all participants. Overall, the whole experiment including informed consent, preparation, task performance, and debriefing took approximately 1.5 hours per participant.

Data preprocessing

Python scripts were used for the data preprocessing. Pupil size signals were downsampled and blinks were interpolated. Afterward, the relevant measures were extracted: pre-stimulus pupil size, average baseline, and standard deviation (SD) of baseline pupil size. Pre-stimulus size is defined as the average pupil size one second preceding the presentation of the target. These measures were then converted from arbitrary units to millimeters. Pupil sizes were categorized as 'large' or 'small' depending on whether pupil size was larger or smaller than the median pre-stimulus pupil size for each participant separately.

1/f Noise was continuous between opacity levels 0-0.6 and was later split up in 3 segments: low, medium and high. The low segment consisted of the range 0-0.2, the medium segment of 0.2-0.4 and the high segment 0.4-0.6.

Blocks were analyzed as a whole and divided into early (trial 1-13), middle (14-26) and late (27-40) segments to analyze performance through a block. No steps were taken to remove outliers or edit missing data to maintain the integrity of the data and to avoid potentially altering the natural distribution which could introduce a bias. This means that naturally occurring fluctuations in arousal over the course of the experiment are maintained by not removing any trials.

Analysis

To test all hypotheses SPSS (v.30) was utilized. To analyze the first and second hypotheses the same RM-ANOVA was used. The first hypothesis examined whether an increase in noise level causes a decrease in performance for both large and small pupil data. The second hypothesis examined a difference in performance between large and small pupil data. Finally, a separate RM-ANOVA for the third hypothesis was used to measure the difference in performance over time through the block segments early, middle and late.

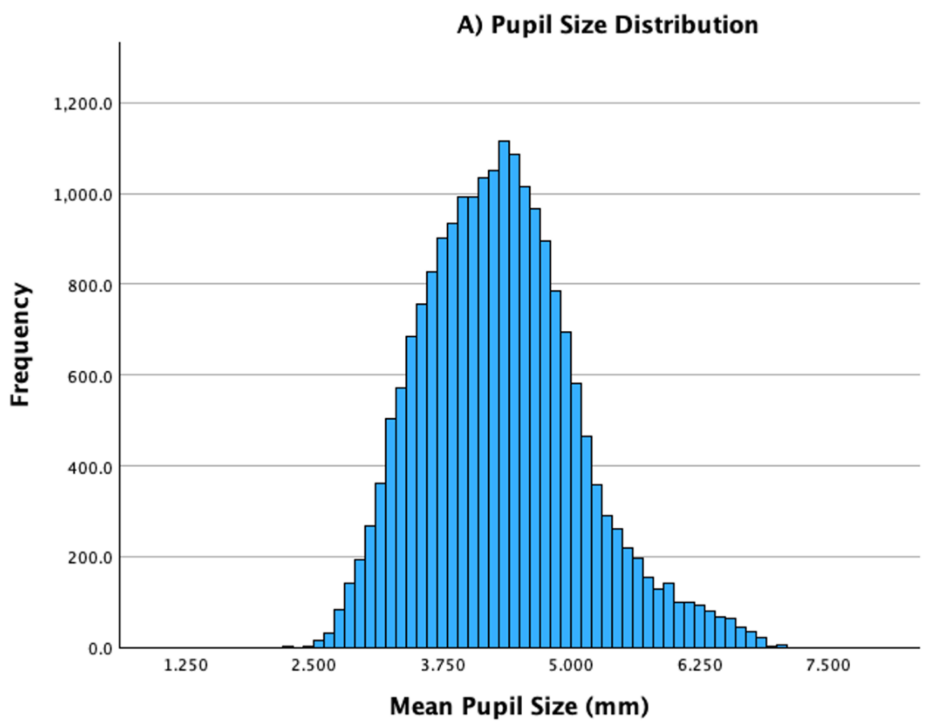
Results

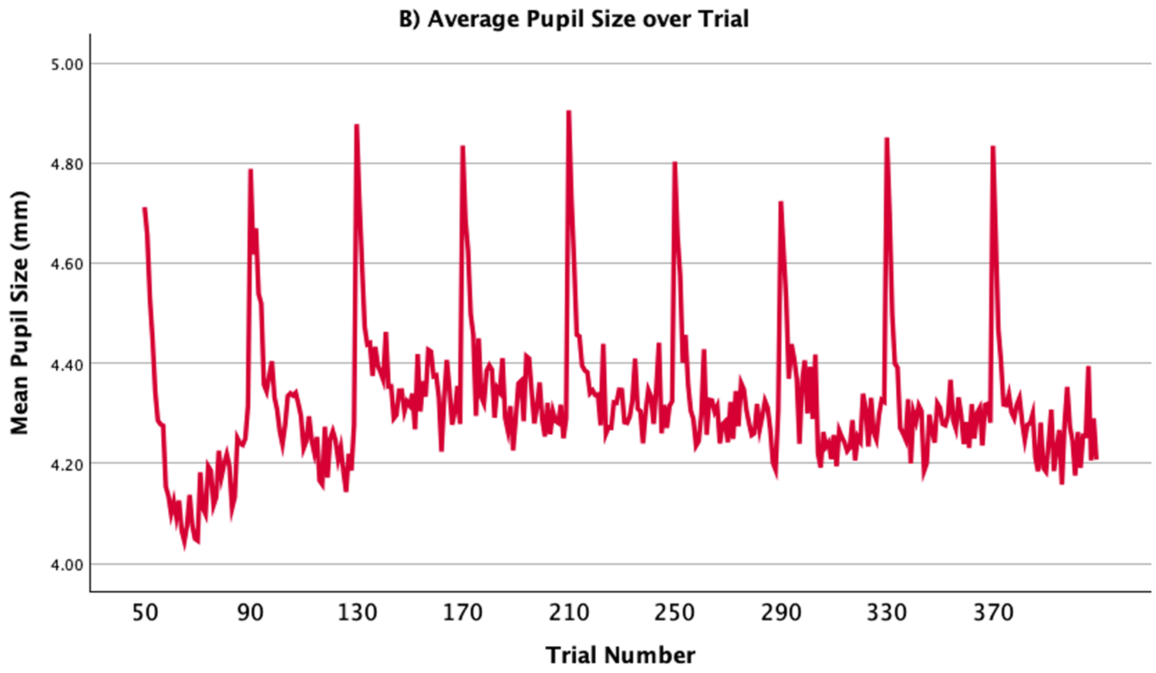
Descriptives: Pupil Size & Performance

Figure 3a shows the distribution of recorded pupil sizes during the experiment. Average pupil size was larger at the start of each block (Figure 3b). Average small pupil size is M_{small} = 3.975 (SD_{small} = .659) and average large pupil size is M_{large} = 4.666 (SD_{large} = .702) in millimeters.

Overall average accuracy, defined as correct hits & rejections (correct hits indicating answering 'yes' when a target is present and correct rejections indicating answering 'no' when no target is present) is M = .74 (SD = .437). Overall accuracy for large pupil data was higher M_{large} = .79 (SD_{large} = .406) than small pupil data M_{small} = .70 (SD_{small} = .460).

Figure 3: Pupil Size Descriptives. A) Pupil Size Distribution. B) Average Pupil Size over time.





Performance Decreases as Noise Level Increases for Both Large and Small Pupils

A RM-ANOVA was conducted with two within-subject factors that had 2 levels indicating large or small pupil size, and 3 levels for noise levels low, medium and high. A significant main effect of noise was found for large pupil size, $F(1.566, 87.694) = 373.210$, $p < .001$, $\eta_p^2 = 0{,}870$, indicating a large effect on performance. The Greenhouse-Geisser correction was used to adjust for violations of sphericity. Pairwise comparisons revealed that performance under low noise ($M_{low} = .927$, $SD_{low} = .041$, $p < .001$) was significantly higher than under medium noise ($M_{medium} = .767$, $SD_{medium} = .064$, $p < .001$) and performance under medium noise was significantly higher than under high noise ($M_{high} = 0.579$, $SD_{high} = 0.079$, $p < .001$).

A significant main effect of noise was found for small pupil size, $F(2, 112) = 383.822$, $p < .001$, $\eta_p^2 = 0{,}873$, indicating a large effect on performance. Pairwise comparisons revealed that performance under low noise ($M_{low} = .896$, $SD_{low} = .072$, $p < .001$) was significantly higher than under medium noise ($M_{medium} = .730$, $SD_{medium} = .055$, $p < .001$) and performance under medium noise was significantly higher compared to high noise (M_{high} = .559, SD_{high} = .045, $p < .001$).

Improved Performance with Larger Pupil Size Compared to Smaller Pupil Size

The same RM-ANOVA was used to test the significance of the observed difference in the effect of pupil size and noise level on visual detection performance. Results showed a significant main effect of pupil size, $F(1, 56) = 26.768$, $p < .001$, $\eta_p^2 = .323$, indicating that participants performed significantly better with large pupils compared to small pupils.

However, the interaction between pupil size and noise level was not significant, $F(2, 112) = .994$, $p = .373$, $\eta_p^2 = .017$, indicating that the effect of pupil size on performance did not significantly vary across noise levels.

Performance over Time

Finally, a separate RM-ANOVA was conducted to examine the visual detection performance over time in a block of trials through the segments early, middle and late. No significant main effect was found for the segments, $F(1.754, 98.233) = 1.469$, $p = .236$, $\eta_p^2 = .026$, indicating that no significant difference was found between the three segments. Although the analysis revealed no significant effect, the early segment did show the highest mean (M_{early} = .751) compared to the middle segment (M_{middle} = .74) and late segment (M_{late} = .74).

Discussion

This study investigated whether pupil size affects visual detection performance at different levels of external noise. Using a within-subjects design, participants completed a visual detection task modified with varying levels of 1/f noise. Performance was analyzed using RM-ANOVAs. Three hypotheses were proposed: first, that visual detection performance would decrease as noise level increased, second, that performance would be significantly better when participants had larger pupil sizes compared to smaller pupil sizes, and third, that performance would be higher at the start of a block of trials and decrease over time.

The results provided support for the first two hypotheses. Analysis of the first hypothesis revealed that performance significantly decreased across all noise levels for both large and small pupil size trials, indicating a robust main effect on visual detection performance. Secondly, the analysis of the second hypothesis found that participants performed significantly better when their pupil sizes were larger compared to smaller pupil sizes, regardless of noise level. However, there was no significant interaction between pupil size and noise level. The analysis of the third hypothesis found no significant difference between the three segments in a block.

The findings of this study contribute to the growing body of research in pupillometry. This study is the first to explore the effects of pupil size on visual detection performance with external noise levels. As noise level increases and SNR decreases, the tasks get more perceptually demanding for participants to differentiate between noise and target, which results in increased difficulty to detect the stimuli. The results do align with previous studies (Ivanov & Mathôt, 2019; Eberhardt et al., 2021) that large pupils are associated with improved detection of faint stimuli in peripheral vision compared to small pupils. This advantage seems to persist regardless of noise level, suggesting that pupil size is a stable factor of visual sensitivity.

The lack of an interaction effect presents an interesting finding. As lighting conditions for the experiment were constant, pupil size changes cannot be attributed to the PLR. Therefore, I can focus on the role of cognitive-driven pupil size changes. The absence of an interaction effect suggests that pupil dilation enhances visual detection performance evenly across noise levels, independent of the increased task demands introduced by external visual noise.

This result may be explained through the relationship between arousal and performance. First, I propose that the current visual detection task with external visual noise is likely more arousing compared to the classic visual detection task without noise as the task has become more visually demanding. Doll et al. (2024) found that pupil dilation, indexed as arousal and sustained attention, had an inverted U-shaped relationship with performance. Additionally, Ruuskanen et al. (2024) also found an inverted U-shaped relationship with pupil size and sensitivity, which might be driven by arousal and optical effects. These findings align with the Yerkes-Dodson Law, which states that performance improves with increasing arousal until it reaches an optimal level, after which it declines (Yerkes & Dodson, 1908).

I propose that this plateau effect could be attributed to the limits of early noise processing and cognitive processing. Silvestre et al. (2018) found that early noise processing can degrade contrast sensitivity in a linear way at low luminance levels. One could speculate that when arousal levels become too high, early noise processing is overwhelmed leading to a plateau effect. If internal noise is excessive, this diminishes the ability to effectively detect contrasts, thus limiting performance despite increased arousal.

The insignificant results for performance over time may suggest that performance is stable throughout a block. However, to nuance these findings, it is important to highlight that the results provided support for the second hypothesis, which served as a basis for the third hypothesis. Second, the spike and habituation effect in pupil size through auditory noise reported by Antikainen & Niemi (1983) was replicated for external visual noise (figure 3b). Although the early segment showed the highest mean performance compared to the middle and late segments, these differences were not statistically significant. Future research incorporating adjusted analyses of performance over time may provide further insight into potential significant declines in performance.

This study contributes to the theoretical understanding of the effect of pupil sizes. The results reinforce the concept that a large pupil size is associated with better visual detection performance. This finding even holds true across different levels of external visual noise.

In terms of practical implications, these findings suggest that pupil sizes should be considered in the design or performance of tasks in noisy environments. Understanding and communicating how pupil size influences detection in high noise environments, like for instance aviation or driving, could help create more awareness for visual sensitivity and detection. Adjusting lighting conditions or display interfaces to optimize visual sensitivity, and in return optimize performance, could enhance safety.

While this study provides new insights into the relationship between pupil size and visual detection performance, limitations must be acknowledged. Generalizability could be limited due to the sample size consisting exclusively of first-year psychology students at the University of Groningen, who also received course credits for participating. The task design may also lack ecological validity as a real-world visual detection scenario could be more complex. Third, the range in time segments of a block could have impacted the analysis in performance over time.

Future research could build on the current study by addressing several areas. Enhancing generalizability by a larger exploration of demographic factors would allow for more nuanced results. Second, improving the visual detection task by adding more realistic and dynamic environments, adding a wide range of noise levels would result in additional depth. Adding emotional aspects into stimuli could provide further insights into this complex field as observing positive or negative visual stimuli can result in dilation of the pupil (Bradley et al., 2008). Third, a more thorough exploration of performance over time could result into new insights, by for instance making blocks with longer trials or shortening the length of the early segment. Finally, the absence of the interaction effect between pupil size and noise levels presents an intriguing question. Examining the neurocognitive mechanisms behind pupil size and noise processing further, could reveal if arousal can overwhelm early noise processing. The EEG research by Ruuskanen et al. (2024) suggests that cortical excitability and pupil size interplay on visual detection depend on different neural systems, thus such an exploration for pupil size and noise processing seems fitting.

This study offers a novel perspective on the influence of pupil size on visual detection with the addition of visual external noise. This research highlights the independent effects of pupil size and external visual noise and opens new dimensions to understanding visual processing, further advancing our understanding on human perception.

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