Tracking Covert Attention in Complex Stimuli with Pupil Size Changes

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Abstract

Covert attention, the ability to attend to spatial locations without making eye movements, is categorized into endogenous and exogenous types. The pupil light response (PLR) has been shown to be modulated by covert attention, with changes in pupil size reflecting the luminance of attended stimuli when the stimuli are simplistic. This study aimed to determine whether covert attention could be effectively studied using pupil size changes and the Open Dynamic Pupil Size Modeling (Open-DPSM) toolkit. Thirty-six participants viewed 32 movie clips. Behavioral data confirmed the successful manipulation of attention, with better performance on the attended side. Significant correlations between horizontal pupil bias and hit rate bias indicated that behavioral and physiological measures align with the instructed attentional deployment. Horizontal pupil bias differences in different attended conditions demonstrated endogenous covert attention. Finally, sides with stronger visual events exerted a higher influence on the PLR than the side with weaker events, demonstrating exogenous attention. Together, these findings suggest that the Open-DPSM toolkit can measure covert attention via the PLR in complex stimuli such as movies, demonstrating consistent effects of both endogenous and exogenous attention.

Keywords: pupil size changes, pupil light response, Open-DPSM toolkit, pupillometry, endogenous covert attention, exogenous covert attention

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Visual Spatial Attention

Attention is a crucial component of visual perception that enables us to efficiently process and prioritize visual information. It allows us to selectively process information and prioritize cognitive and visual effort which allows us to handle visual information efficiently and meaningfully (Carrasco, 2011; Cave, 2015; Vecera & Rizzo, 2003). Visuospatial attention, one type of attention, is crucial for selecting and processing visual stimuli based on their spatial location. Displacing spatial attention allows for the processing of visual information with greater detail and accuracy. This is achieved by directing the fovea, the part of the retina with the highest spatial resolution and sensitivity to fine details, towards different locations (Cave, 2015).

While directing gaze improves the processing of visual information at the point of focus, researchers have also recognized and studied the ability to direct attention spatially without moving the eyes for over a century. In the 1860s, Hermann von Helmholtz looked through a wooden box through two pinholes and directed his attention to specific regions of his visual field without moving his eyes. When a light shortly illuminated the box, he observed that he could perceive objects in the region he attended more than the unattended, without the possibility for any eye movements. This experiment was of the earliest recorded that demonstrated that attention could be directed independently of eye position and accommodation (Helmholtz, 1896, as cited in Nakayama & Mackeben, 1989; Carrasco, 2011). These two processes are now referred to as overt attention, which involves explicit eye movements, and covert attention, which involves directing attention without any eye movements (Shulman et al., 1979; Posner, 1980).

Covert attention plays a critical role in various cognitive processes and everyday activities. It can reduce the need for costly saccades by preceding eye movements, which allows individuals to monitor the environment without making frequent saccades, effectively guiding the next gaze (Ebitz & Moore, 2019; Koevoet et al., 2023). This mechanism is also useful in daily activities such as in driving (Tuhkanen et al., 2019), in social interactions (Dosso et al., 2020), or even in consumer decision-making (Perkovic et al., 2023). Additionally, covert attention enhances perceptual benefits (e.g., contrast sensitivity), as attended stimuli receive preferential processing (Carrasco & McElree, 2001; Carrasco et al., 2004; Carrasco, 2014; Carrasco, 2018). These findings highlight the significant role of covert attention in visual perception.

Endogenous and Exogenous (Covert) Attention

William James (1890) originally described two distinct kinds of attention: one as passive and involuntary, and the other as active and voluntary. These two mechanisms are now referred to as exogenous (or transient) and endogenous (or sustained), respectively. Endogenous attention reflects a top-down deployment of (covert) attention, driven by goals and information (Carrasco, 2011; Corbetta & Shulman, 2002; Nakayama & Mackeben, 1989). For example, knowing or expecting an image to appear at a certain location, one can direct their attention to that location, without moving their eyes. In contrast, exogenous attention reflects a bottom-up deployment of (covert) attention, driven by saliency and or intensity (Nakayama & Mackeben, 1989), in other words, by the stimulus itself. For instance, a bright light appears in a peripheral location that attracts attention towards it (Jonides & Irwin, 1981), without explicit eye movement to that location.

Pupillometry as a Measure of Underlying Cognitive Processes

History of Pupillometry in Cognition

The pupil light response is a physiological mechanism where the pupil size changes in response to varying light conditions (Ellis, 1981; Loewenfeld, 1999). This reflex aims to balance the amount of light entering the eye and visual acuity (Campbell & Gregory, 1960). While traditionally pupil size changes were thought to be solely influenced by low-level factors such as light levels, when light enters the eye, it is converted to electrical impulses by retinal cells, which then travel through the optic nerve to the brain, influencing pupil constriction. Thus, the PLR involves a complex interaction of neural pathways, leading to modulations in its response to light and pupil size by cognitive processes (Carrick et al., 2021), so much so that sources of brightness can constrict the pupil even if they are merely read about (Mathôt et al., 2017) or imagined (Laeng & Sulutvedt, 2014).

Accordingly, pupillometry, the measurement of pupil diameter, has significantly advanced over the past decades in its application to studying cognitive processes. Recent studies have utilized pupillometry to investigate a wide range of cognitive functions, including memory (Heaver & Hutton, 2011; Otero et al., 2011), learning (Eldar et al., 2013), affective processing (Partala & Surakka, 2003), and decision-making (De Gee et al., 2014; Preuschoff et al., 2011). Among these various cognitive processes, attention, notably covert attention, has emerged as a significant area of research (see Strauch et al., 2022; Mathôt, 2018 for a review on the use of pupillometry in psychology and neuroscience).

Pupillometry in Spatial Attention

While visuospatial attention is an integral part of visual perception, its functions may be obscure and challenging to study directly. For instance, perceptual rivalry, a phenomenon where observers experience changes in their perceptual experience when viewing ambiguous or superimposed images (Carter et al., 2020), is a well-documented yet difficult to measure or study. The difficulty arises because the perceptual switches between the stimulus in visual awareness that occur, occur covertly within the brain, while the stimulus itself remains unchanged. Well-known types of perceptual rivalry occur during bistable images, such as the Necker cube (Necker, 1832), an optical illusion where a cube can be interpreted in two different ways, and binocular rivalry (Wheatstone, 1838), where two different images are presented to different eyes and only one becomes dominant. Using pupillometry, researchers were able track perceptual switches during bistable images (Einhauser et al., 2008; Harms, 1937; Naber et al., 2011) as well as during binocular rivalry paradigms (Fahle et al., 2011; Schutz et al., 2018). They found that when participants perceptual experience was of a bright percept, their pupils constricted, whereas when it was of a dark percept, their pupils dilated.

In a similar vein, covert attention shifts, which occur without explicit eye movements, are similarly concealed, making them harder to study physiologically. However, researchers have obtained valuable insight on endogenous covert attention deployment using pupillometry and Posner-cueing (Posner, 1980) paradigms. Specifically, they found that when participants were cued to specific locations (i.e., endogenous covert attention was deployed), the pupil constricted or dilated in response to the luminance of the location (Binda et al., 2013; Haab, 1885; Mathôt et al., 2013). Furthermore, employing variations of the Posner-cueing task and pupillometry, where participants were not endogenously cued but instead stimuli exogenously attracted their attention to either a bright or dark location, researchers have also been able to uncover exogenous shifts of covert attention (Mathôt et al., 2014; Wagenvoort et al., 2022). Thus, taken together, these studies reveal that the PLR is driven not only by what we look at directly, but also what we covertly attend to, both endogenously (voluntarily) and exogenously (involuntarily) and by measuring changes in pupil size, researchers can infer the allocation of covert attention, making the invisible visible.

The Open-DPSM Toolkit and Complex Stimuli

The complexity behind pupil size changes, influenced by multiple factors (Mathôt, 2018; Strauch et al., 2022), poses challenges to effectively studying covert attention using complex or dynamic stimuli. While the significant contributions of previous research have demonstrated that the pupil light response (PLR) can reflect covert attention, these studies often relied on simplistic stimuli such as black-and-white patches or required behavioral responses (Binda et al., 2013; Haab, 1885; Mathôt et al., 2013; Naber et al., 2011; Strauch et al., 2022; Ten Brink et al., 2023). In light of these challenges, the Open Dynamic Pupil Size Modeling (Open-DPSM), an open-source toolkit designed by Cai et al. 2023, represents an advantage in pupillometry and attention research.

The toolkit enables the exploration of attention deployment across complex, and dynamic stimuli, such as movie clips. This is achieved by extracting visual events from individual frames of gaze-contingently, ensuring that the data reflects the participant's actual visual experience, it then estimates the relative influence of visual events, such as changes in luminance, across different regions of the visual field on pupil size and fits a predictive model of expected pupil response. A key benefit of using the toolkit is its ability to investigate both endogenous and exogenous attention through pupil size changes, providing a more nuanced understanding of attentional deployment, while also eliminating the need for behavioral feedback and offering a direct and physiological measure of attention.

Current Study

This study used pupillometry and the Open-DPSM toolkit to investigate whether covert attention can be effectively studied through pupil size changes while viewing complex, dynamic stimuli like movie clips. Specifically, the aim was to determine if both endogenous (top-down) instructed covert attention affected pupil size weights in the expected direction and if stronger visual events on one side are associated with higher weights for that side, effectively revealing exogenous (bottom-up) covert attention.

To verify that the attentional manipulation and task were successful, it was hypothesized that hit rates would be significantly higher in the left and right conditions compared with the corresponding side in the both condition (H_1). Additionally, to ensure that both behavioral and physiological measures align with the instructed task, it was hypothesized that horizontal pupil bias would be positively correlated with hit rate bias (H_2). To address endogenous attention, it was hypothesized that horizontal pupil bias would differ significantly between the attended and unattended sides (H_3). For exogenous attention, it was hypothesized that there would be a significant positive correlation between horizontal pupil bias and contrast events (amplitude and number of contrast events) (H_4).

Method

Participants

All experimental procedures were approved by the Ethical Review Board of the Faculty of Social and Behavioral Sciences at Utrecht University (approval number 24-0064). Participants were recruited via word-of-mouth and flyers posted around the Utrecht University campus and shared on social media platforms. The study included 38 adults with normal or corrected-to-normal vision, aged between 19 and 30 years. There were no additional eligibility criteria for participation beyond restrictions related to avoiding nicotine, caffeine and eye make up on the day of participation. Participants who failed to follow instructions were excluded from the final analysis (*n* = 2), resulting in a total of 36 participants in the final analysis (*n* = 36, M_{age} = 24.33, SD_{age} = 2.92 years). Regarding demographics, 77.78% were females-at-birth and 22.22% males-at-birth, 91% right-handed and 8% left-handed, and finally regarding language proficiency, 22.22% native Dutch speakers, 13.89% basic to intermediate Dutch proficiency and 61.1% spoke no Dutch. Participants were compensated with either 8€ per participation hour or 1 PPU if they were Psychology bachelor students at Utrecht University, as participation credit.

Materials

Stimuli

A set of 32 sixty-second clips were selected from Gestefeld et al. (2021; original stimuli can be retrieved from DataVerseNL, https://doi.org/10.34894/LEYVL8) and then customized to create a set of 64 unique movie clips for this experiment. The initial customization process involved preparing the movie clips:

Cropping. The first step involved cropping the movie clips so that they were all standardized to 16:9 aspect ratio (1920x1080 pixels), ensuring that all movies were presented at 60.3° of horizontal visual angle and 33.75° of vertical visual angle from the participant.

Mirroring. A "flipped" version of each of the 32 cropped movies was generated. This involved horizontally flipping each clip along with their audio channels, creating a mirrored counterpart. This manipulation controlled for imbalances in the stimuli by ensuring that visual events were evenly distributed across the left and right visual fields for all participant groups, allowing observed effects in top-down attention to be confidently attributed to the experimental conditions rather than the stimulus material itself.

Overlaid Elements. Additional elements were overlaid on the movie clips using Python and PsychoPy. A magenta ([255,0,255] in RGB) fixation cross was placed at the center of the screen to help participants maintain their central gaze. The cross measured 30 pixels in both length and width, at 1.71° visual angle. Two Gabor gratings were added to each side of the clip, allowing participants to covertly attend to the left, right, or both sides depending on their condition. The gratings were black and white, concentric patterns, each 15 pixels in size with an opacity of 0.4. The gratings moved continuously and stopped three to eight times during each movie which participants were asked to respond to. The motion paths and stop points were randomly selected from predefined regions, with the gratings positioned between 16° to 23° eccentricities from the center on each side. During the experiment, additional rectangular extensions were added to the central fixation cross in PsychoPy dependent on the participant's condition. These magenta ([255,0,255] in RGB) extensions, each 17 pixels in width and 13 pixels in height, were positioned on the left, right, or both sides of the cross indicating the task condition. For an illustration, see Figure 1 below.

Figure 1

Sample Stimuli Presentation During a Trial

Note. This figure illustrates a sample frame from a trial. The overlayed orange elements are not apparent during the trial but displayed here to illustrate the motion paths, required gaze position, and eccentricities at which the gratings are presented relative to the central fixation point. The central magenta fixation cross is present during the trial cross helps participants maintain their gaze at the center of the screen, as well as the condition specific extension aiming to the condition side (right in this sample). Two faded Gabor gratings are visible on the left side at 16° eccentricity and the right side at 23° eccentricity.

Apparatus

The experiment utilized a 65-inch LG OLED65B8PLA TV with dimensions of 145 by 80 cm, providing an 88.1° by 56.1° visual angle. The TV displayed stimuli at a resolution of 1920x1080 pixels and a refresh rate of 100Hz. The maximum brightness of the TV was 212 cd/m² with a gamma setting of 2.2. Binocular eye movement and pupil size data were recorded using a tower-mounted EyeLink 1000 system (SR Research) at a sampling rate of 500 Hz.

Participants' heads were stabilized using a chin and forehead rest positioned 75 cm from the screen. The eye tracker employed circular fitting to measure pupil diameter. A computer equipped with PsychoPy (version 2022.2.4) controlled the TV display and interfaced with the EyeLink system. The only ambient light in the room, aside from the movie-displaying TV, was from the EyeLink communication monitor, resulting in light levels of less than 1 Lux, which minimized any potential light interference.

Experimental Design

The experiment utilized a 2x4 mixed design. The within-subjects factor included four distinct conditions (left, right, both and none) with tasks, while the between-subjects design was a divided assignment to two separate stimuli sets (‘flipped’ or ‘not flipped’). All conditions required central gaze fixation within a 50-pixel border at 2.88° of visual angle around the central fixation cross. If participants spent more than 20% of the trial time outside this area, they were given a warning and would repeat the trial.

Within-Subjects Conditions

Each participant completed eight trials for each of the four conditions (left, right, both, and none), for a total of 32 trials. Within these conditions, participants were instructed to direct their covert attention (i.e., without making an eye movement) to specific regions based on the condition and had to respond to pauses in the respective grating(s)’ motion with a keypress. The task was used to ensure participants maintained their endogenous covert attention as they were instructed to. The order of condition presentation was counterbalanced by randomizing the sequence per participant. The specific task and instructions per condition can be found in Appendix.

Between-Subjects Sets

Each participant was assigned to one of two groups: “flipped” or “not flipped”. These groups viewed either a mirrored or a normal set of stimuli, respectively. This manipulation evenly distributed visual events across the left and right visual fields. The design controlled for inherent biases in the visual stimuli, allowing the attribution of changes in pupil size to attentional processes.

Procedure

Experimental Procedure

Upon arrival at the Utrecht University’s Experimental Department, participants were guided to the laboratory. They were given an information letter and consent form to read and sign if they had agreed to participate. Basic demographic information was collected, including age, sex at birth, Dutch proficiency, and any current medication use. Participants were seated comfortably in front of the Eye Link Eye Tracker, and the lighting was adjusted. The eye tracker was calibrated using a 5-point calibration and 6-point validation process. Additionally, participants were instructed to alternate which hand they used for responses after every four trials to eliminate any possible dominant hand bias or stimulus response compatibility (S-R) effects (Fitts & Seeger, 1953) to stimuli on the same side as the responding hand (e.g., right hand responding to right-side stimuli).

Participants were then assigned to conditions and provided with the instructions relating to which gratings to covertly attend to, what their task was and which hand to use for the first trial. The researcher monitored the eye-tracking data to ensure participants maintained their central gaze as well as ensure there were no other issues coming up. Calibration and validation checks were performed regularly, typically every four trials, or as needed if the participant moved or experienced discomfort.

Ethical Considerations

This research posed no risk of harm or discomfort unusual to everyday life. Participants were fully informed about the study's purpose, procedures, and their rights. Personal data capable of identifying participants was not recorded, ensuring anonymity. Participation was voluntary, and they could withdraw at any time without providing a reason.

Data Analysis

The primary objective of the data analysis was to examine the relationship between covert attention deployment and changes in pupil size from both top-down and bottom-up perspectives. The main tool used to extract visual event information and model pupil size changes from the movies and eye tracking data was the Open-DPSM toolkit, and further data analyses were conducted using Python. The visual field weights, as obtained from the toolkit, should indicate how strongly these visual events influenced pupil responses relatively. These weights should then allow the inference of where covert attention was directed, as an effect of endogenous and exogenous covert attention on pupil size changes.

Preprocessing and Data Preparation

The data analysis involved several key preprocessing steps to prepare the data for modeling and analysis. The first steps involved cleaning repeated trials. The raw data from the EyeLink eye tracker was then processed to extract the necessary data. After this, the eye tracker files were processed to interpolate missing blinks in the pupil trace and saccades. Trials with more than 30% missing data were excluded from the final analysis.

Open-DPSM (Event Extraction and Modeling)

The Open-DPSM toolkit (Cai et al., 2023), was employed to model pupil size changes in response to dynamic visual stimuli. This toolkit allows for the estimation of the relative influence of visual events (e.g., changes in luminance) on pupil size changes, quantified and weighted across 44 regions of the visual field. The modeling used the previously customized movie clips and gaze contingently extracted visual events to account for deviations in gaze position from the central fixation cross as well as to consider the overlaid elements. The model fitted pupil size changes based on the extracted events, with regional weights indicating the extent to which each region in the visual field influenced the pupil size changes, thereby reflecting covert attention deployment. The model's performance was evaluated using correlation coefficients (r), with r = 0.55 to 0.75 indicating good model performance. For more on the modeling process, see Cai et al. 2023.

Key Variables

Horizontal Pupil Bias. The horizontal pupil bias (HPB) is calculated using the regional weights provided by the Open-DPSM. Specifically, the weights of the left and right visual field regions are summed first for each side and then the differences are computed (right - left). Thus, negative values represent a leftward pupil bias while positive values represent a rightward pupil bias. This variable measures the relative amplitude of the pupil response, which should indicate the direction and strength of attention shifts.

Hit Rates. The hit rates were calculated for each non-passive condition (left, right and both). For the left condition, the hit rate for the left side was computed by dividing the number of hits by the number of stops for that side. Similarly, for the right condition, the hit rate for the right side was calculated by dividing the number of hits by the number of stops for that side. In the both condition, hit rates were calculated separately for each side using the same formula.

Hit Rate Bias. Behavioral data was also quantified by calculating the hit rate bias. The hit rate bias is a measure of the participant's tendency to detect stops on one side more than the other. It was computed by taking the difference between the hit rates on the right and left sides (right - left), thus negative values indicate a bias to detecting stops on the left side, while positive values mean indicate a bias towards detecting stops on the right side.

Contrast Events Biases. Contrast event biases were of two types: the number of contrast events bias and the amplitude of contrast events bias. The Open-DPSM toolkit was used to extract both the number and the amplitude of contrast events from the visual field regions. The number of contrast events bias was calculated by comparing the *number* of luminance changes (contrast events) detected on the right and left sides (right - left), measuring the frequency of contrast events on the right versus the left side. The amplitude of contrast events bias was determined by calculating the difference in the *strength* of luminance changes between the right and left sides (right - left), indicating the relative strength of luminance changes on the right versus the left side.

Attention Manipulation

Hit rates on the left and right sides were aggregated across the left and right conditions and compared with the corresponding side's hit rates in the both condition, hypothesizing that hit rates would be significantly higher in the left and right conditions compared with the both condition (H_1) to validate the endogenous attentional manipulation. Additionally, a correlation analysis between hit rate bias and HPB was conducted to confirm that participants' horizontal pupil bias was aligned with their behavioral responses (H_2), reflecting the same endogenous bias.

Endogenous Effects

To address endogenous attention, paired t-tests were applied to assess whether there was a significant difference in HPB between the left and right conditions, indicating the ability to trace endogenous covert attention using pupil size changes (H_3).

Exogenous Effects

Correlations were calculated between HPB and biases in the number and amplitude of contrast events to test whether the observed pupil size changes reflect low-level visual event changes. This tested the hypothesis (H_4) that there would be significant positive correlations between HPB and these visual features, demonstrating the sensitivity of pupil size changes to exogenous attentional processes.

Results

Model Performance

The model performance was good ($r = 0.7$) and outperformed the results reported in the Open-DPSM toolkit paper ($r \approx 0.49$), suggesting that the model effectively captured the effects of visual events on pupil size.

Descriptive Results

Table 1 presents the descriptive statistics for key variables, including horizontal pupil bias (HPB), contrast amplitude bias, and contrast frequency bias across the four conditions (none, both, left, and right). These statistics provide a summary of the mean (M) and standard deviation (SD) for each variable and condition.

Table 1

Descriptive Results for Key Variables

	Horizontal Pupil Bias		*Contrast Amplitude Bias*		*Contrast Frequency Bias*	
Condition	*M*	*SD*	*M*	*SD*	*M*	*SD*
None	-0.002	0.004	54.555	443.668	5.583	41.829
Both	-0.002	0.006	-29.794	410.659	-4.751	43.078
Left	-0.005	0.005	-12.838	412.907	2.815	42.169

Right	-0.001	0.005	0.574	402.229	-1.887	43.049

Note. Descriptive statistics showing the mean (*M*) and standard deviation (*SD*) for horizontal pupil bias (HPB), contrast amplitude bias, and contrast frequency bias are presented for each condition (none, both, left, and right). Negative HPB values indicate a bias towards the left side, while less negative or positive values indicate a bias towards the right side. Positive contrast amplitude bias values indicate stronger visual events on the right side, while negative values indicate stronger visual events on the left side. Positive contrast frequency bias values indicate a higher frequency of visual events on the right side, while negative values indicate a higher frequency of visual events on the left side.

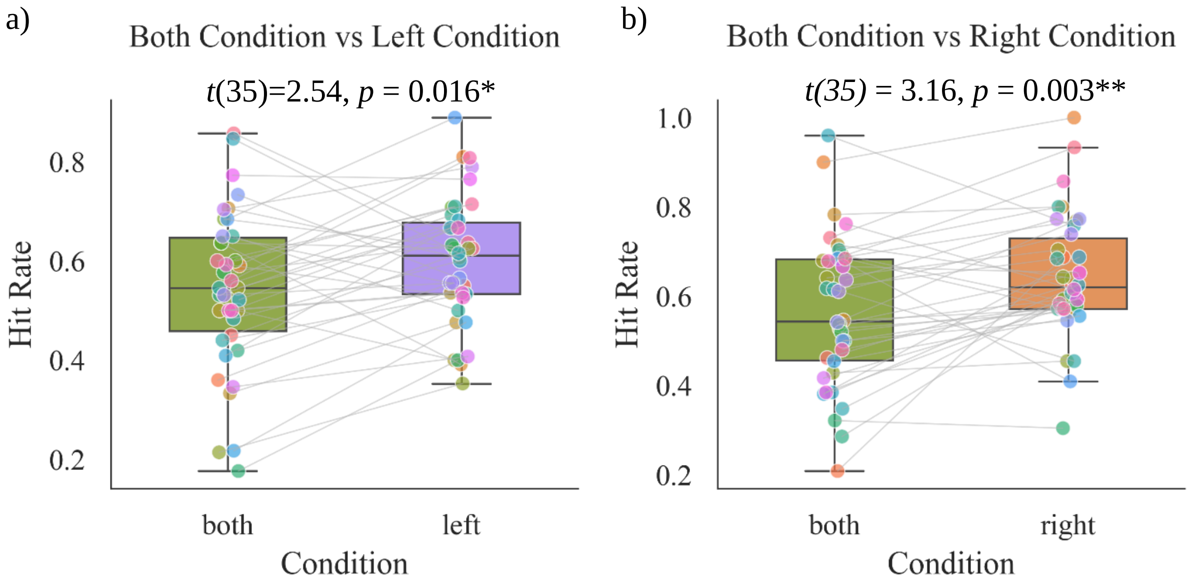
Attention Manipulation

Hit Rates by Side and Condition

Paired-samples t-tests were conducted to compare hit rates between conditions to determine if participants attended more to the instructed side. For the left side, a significant difference was found between the left condition (*M* = 0.567, *SD* = 0.386) and the both condition (*M* = 0.554, *SD* = 0.259); *t*(35)=2.54, *p* = 0.016. A significant difference was also found between the right condition (*M* = 0.654, *SD* = 0.316) and the right side in the both condition (*M* = 0.554, *SD* = 0.259); *t(35)* = 3.16, *p* = 0.003. This indicates that the hit rate was significantly higher in the right condition compared to the right side in the both condition. These results confirm that participants attended more to the instructed side, validating the effectiveness of the attentional manipulations and supporting H_1 for the left and right sides. Refer to Figure 3 for a visual representation.

Figure 3

Hit Rates by Side and Condition



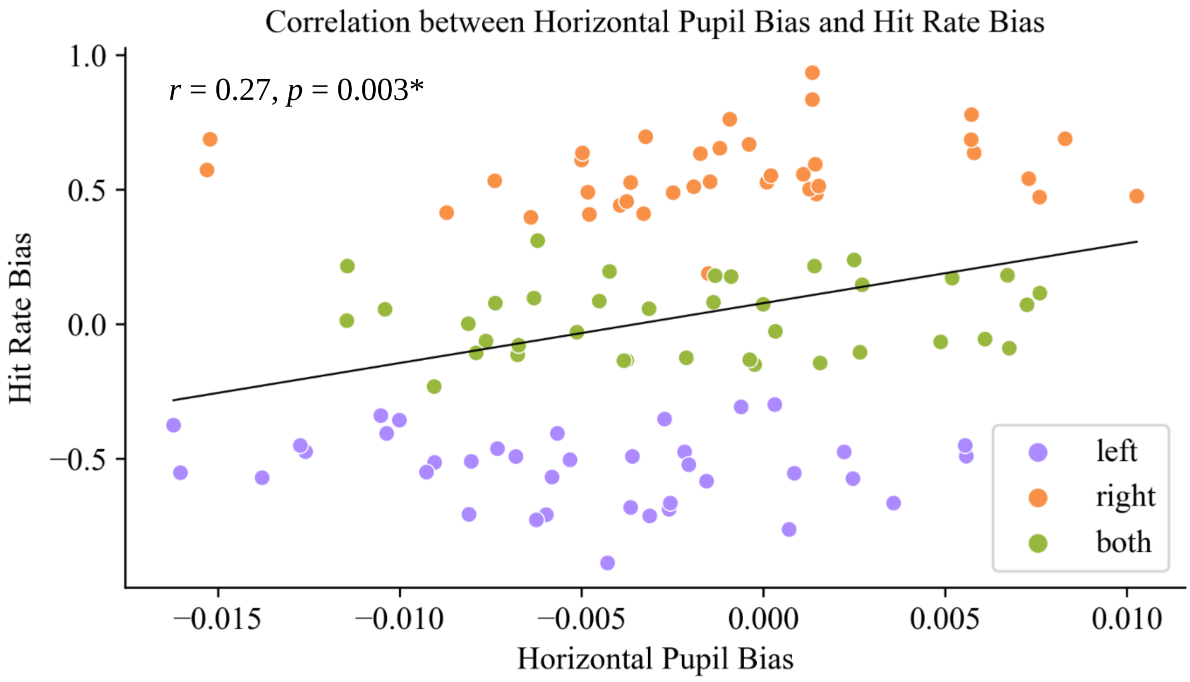
Note. The box plots compare hit rates for the left and right sides between different conditions. Each data point represents an individual participant, with colors indicating different participants. The left graph compares the hit rates for the left side between the left condition and the both condition, while the right graph compares the hit rates for the right side between the right condition and the both condition. The significant differences in hit rates confirm that participants attended more to the instructed side, confirming that attentional manipulations were effective.

Horizontal Pupil Bias and Hit Rate Bias

A Pearson correlation analysis revealed a significant positive correlation between horizontal pupil bias (HPB) and hit rate bias, $r = 0.27$, $p = 0.003$. This indicates that participants who showed a greater bias in their pupil size towards one side (left or right) also demonstrated a higher hit rate on that same side, supporting H_2. These findings further support the relationship between pupil size changes and attentional shifts. Refer to Figure 4 for a visual representation of the correlation.

Figure 4

Correlation between Horizontal Pupil Bias and Hit Rate



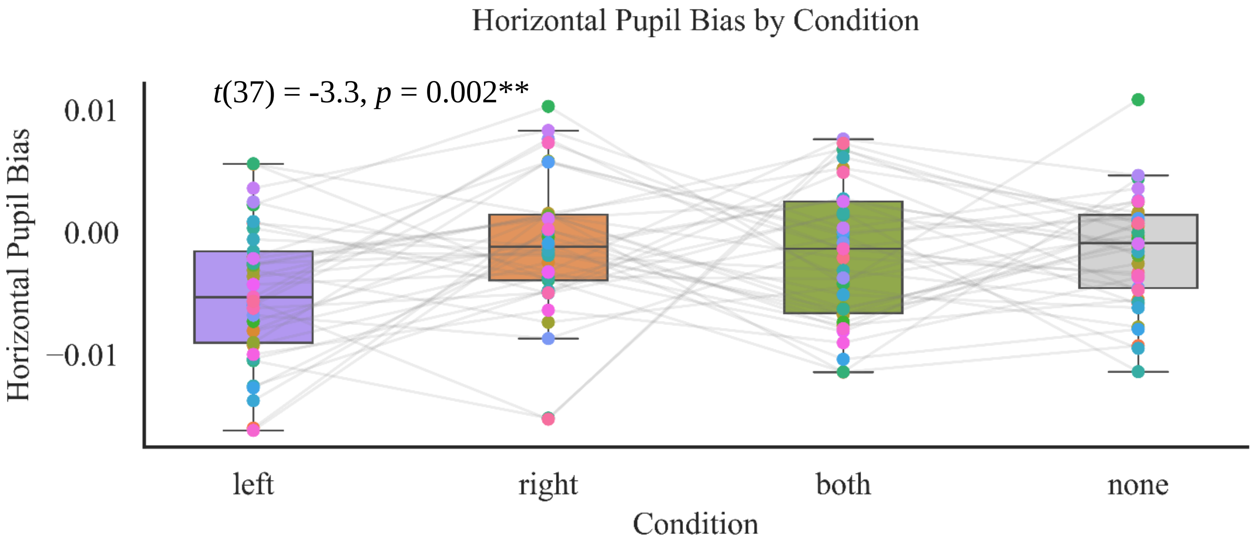
Note. The scatter plot shows the relationship between horizontal pupil bias and hit rate across different conditions. Each data point represents the aggregated data for a participant in a specific condition, with colors indicating the condition: purple for the left condition, orange for the right condition, and green for the both condition. The x-axis represents the horizontal pupil bias values, with points to the left of zero indicating a leftward bias and points to the right of zero indicating a rightward bias. The y-axis represents the hit rate, indicating the proportion of correctly detected targets, with positive values indicating higher hit rates.

Endogenous Covert Attention

A series of paired-samples t-tests were conducted to compare horizontal pupil bias across different conditions. Firstly, there was a significant difference in the horizontal pupil bias between the left condition (*M* = -0.005, *SD* = 0.005) and the right condition (*M* = -0.002, *SD* = 0.005); *t*(37) = -3.300, *p* = 0.002, Cohen's *d* = 0.53). The negative mean value in the left condition and the less negative mean value in the right condition indicate that the bias was stronger towards the left side, matching expectations that instructed attention would affect pupil weights in the expected direction and supporting H_3. Additionally, comparisons between the left condition and the both and the none conditions showed significant results. For the left versus both conditions, *t*(37) = -2.530, *p* = 0.016, Cohen's *d* = 0.41, indicating a stronger bias in the left condition (*M* = -0.005, *SD* = 0.005) compared to the both condition (*M* = -0.002, *SD* = 0.006). Similarly, for the left versus none conditions, *t*(37) = -3.520, *p* < 0.001, Cohen's *d* = 0.57 the left condition showed a stronger bias than the none condition (*M* = -0.002, *SD* = 0.004). Further comparisons revealed no significant differences between the right and both conditions, *t*(37) = 0.610, *p* = 0.544, nor between the right and none conditions, *t*(37) = 0.570, *p* = 0.570. There was also no significant difference between the none and both conditions, t(37) = 0.300, *p* = 0.769. Refer to Figure 5 for a visual representation.

Figure 5

Horizontal Pupil Bias by Condition



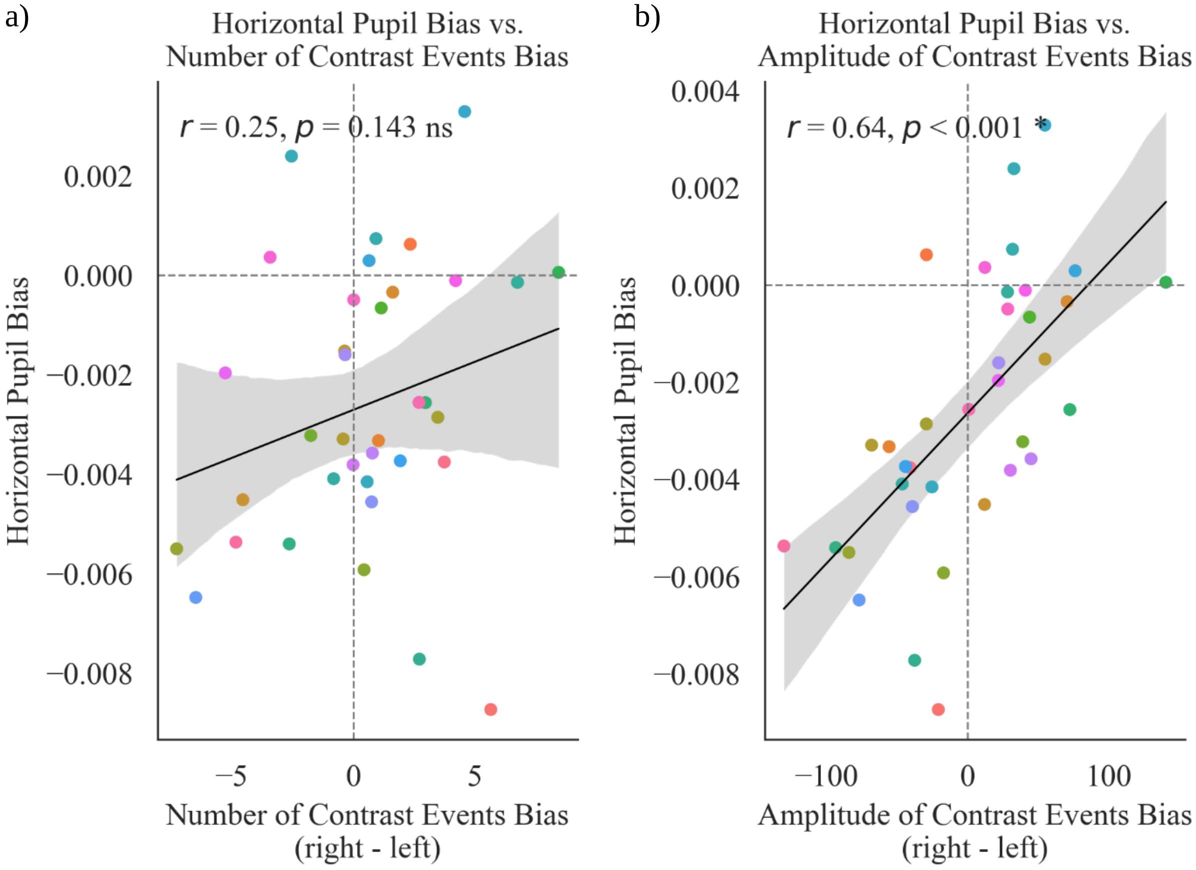
Note. The figure illustrates the horizontal pupil bias across four conditions: left, right, both, and none. Each box plot represents the distribution of horizontal pupil bias for each condition, with the central line indicating the median, the box edges representing the interquartile range, and the whiskers extending to the most extreme data points not considered outliers. Colored dots represent individual participants, with different colors indicating different participants. Gray lines connect the same participants across conditions, showing within-subject variations. The significant differences in horizontal pupil bias, particularly between the left condition and the other conditions, support the hypothesis that instructed attention affects pupil weights, demonstrating a stronger leftward bias in the left condition.

Exogenous Covert Attention

Pearson's correlation tests were conducted to determine the relationships between horizontal pupil bias and two types of contrast events bias: the number of contrast events and the amplitude of contrast events. A Pearson correlation test revealed a non-significant positive correlation between horizontal pupil bias and the number of contrast events bias, $r = 0.25$, $p = 0.143$. These results suggest that variations in the number of contrast events across the visual field did not significantly impact horizontal pupil bias. In contrast, the correlation between horizontal pupil bias and the amplitude of contrast events bias revealed a significant positive correlation, $r = 0.64$, $p < 0.001$. This significant relationship indicates that as the amplitude of contrast events bias increases, the horizontal pupil bias also increases, partly supporting H_4. Refer to Figure 6 for a visual representation of these correlations.

Figure 6

Horizontal Pupil Bias and Contrast Events



Note. The left scatter plot (a) illustrates the relationship between horizontal pupil bias and the number of contrast events bias, showing a non-significant correlation. Each data point represents an individual participant, with different colors indicating different participants. The right scatter plot (b) depicts the relationship between horizontal pupil bias and the amplitude of contrast events bias, highlighting a significant positive correlation.

Discussion

The primary objective of this study was to determine whether endogenous and exogenous covert attention could be effectively studied through attentional modulations of the pupil light response using the Open-DPSM toolkit while participants viewed complex, dynamic stimuli. The results confirmed several key hypotheses, demonstrating that both types of covert attention can be captured using this method.

Validation of Attentional Manipulation

The attentional manipulation was successful, with results showing notably higher hit rates in the side-attended conditions compared to that side in the both sides condition. Moreover, the relationship between HPB and hit rate bias further indicated that when participants were more accurate in detecting targets on a side, their pupil sizes also showed a corresponding bias towards that same side, demonstrating that pupil size measurements aligned with the behavioral measurements.

Validating the task's attentional manipulation was crucial as there is limited research on how long covert attention can be sustained at specific spatial locations, especially with such complex and dynamic stimuli. Furthermore, while it was beneficial for participants to maintain central gaze to effectively study and isolate covert attention and prevent participants from making goal-directed saccades (Carrasco, 2011), sustaining attention at peripheral eccentricities poses challenges due to effects such as Troxler's fading (Troxler, 1804). These findings reinforce the task used in this study as an effective method for prompting and retaining endogenous attention. prompting and retaining endogenous attention.

Endogenous Covert Attention

HPB differences across conditions provided evidence for tracking covert attention using pupil size changes. The differences in HPB between the left and right conditions indicated a stronger leftward bias when participants were instructed to attend on the left side, aligning with expectations that endogenous covert attention deployment can be revealed by examining pupil size changes. These findings align with previous research on covert attention and pupillometry, indicating that pupil size changes can effectively reflect endogenous covert attention (Binda et al., 2013; Binda & Murray, 2015; Haab, 1886, as cited in Strauch, 2024; Mathôt & Van der Stigchel, 2015; Naber et al., 2011; Naber et al., 2013; Salvaggio et al., 2022; Strauch et al., 2022; Ten Brink et al., 2023). Furthermore, comparisons between the none condition and the both condition did not show any differences, indicating that there was no lateral bias in attention distribution when participants viewed freely or attended to both sides, reflecting a neutral allocation of attention to both sides in these conditions.

Intriguingly, comparisons between the right condition and the both condition, as well as the right condition and the none condition, showed no differences in contrast, to comparisons of the left condition with the both condition and the none condition which revealed a pronounced leftward bias. The consistent leftward bias across all comparisons involving the left condition, as opposed to the right condition, may highlight a potential asymmetry in attentional deployment. This may imply that participants found it easier or more natural to shift their attention leftward, or that the leftward bias was more pronounced due to inherent or learned tendencies in attentional deployment. Previous research has suggested that there can be asymmetries in attentional control, with some studies indicating a natural leftward bias in visual attention, known as pseudoneglect (Bowers & Heilman, 1980; Klatt et al., 2024). Furthermore, pseudoneglect has also been previously revealed using pupil size changes (Strauch et al., 2022). Thus, the findings of this study could reflect this inherent bias, which may have been further amplified under explicit leftward attentional instructions.

Exogenous Covert Attention

There was no evidence for a relationship between HPB and the number of contrast events bias, suggesting that the frequency of visual events across the visual field did not drive exogenous attentional shifts as measured by pupil size changes. This indicates that simply having a higher number of visual events on one side is not enough to cause notable shifts in HPB. However, the relationship between HPB and the amplitude of contrast events bias indicated that stronger visual events on one side do cause greater exogenous shifts. This finding suggests that exogenous attention is driven more by the intensity of visual stimuli rather than their frequency, aligning with past literature that reports salient, high-amplitude events capture attention involuntarily (Carrasco et al., 2004; Ling & Carrasco, 2006).

Implications, Applications & Future Directions

As pupil size changes represent a wide array of cognitive processes, researchers have mostly relied on using highly simplistic stimuli to track covert attention in pupillometric studies (Binda et al., 2013; Haab, 1885; Mathôt et al., 2013; Naber et al., 2013). This study, using the Open-DPSM toolkit, supports those findings and further demonstrates that pupil size can be used as a physiological index for covert attention even with more complex and dynamic stimuli. The Open-DPSM toolkit can provide an estimate of expected pupil size changes to stimuli, allowing for the isolation of covert attention. The toolkit can model expected pupil size variations in response to different stimuli, enabling researchers to assess and control for confounding factors related to low-level design elements in pupillometric studies (Cai et al., 2023).

Furthermore, previous research has been able to explore either exogenous covert attention (Mathôt et al., 2014; Wagenvoort et al., 2022) or endogenous covert attention (Binda et al., 2013; Haab, 1885; Mathôt et al., 2013; Naber et al., 2013). The results of this study validate the utility of the Open-DPSM toolkit in capturing the nuances of both endogenous and exogenous attention at once, and further validates pupillometry as a non-invasive tool for studying visuo-attentional mechanisms, offering insights into both top-down and bottom-up processes, contributing to a comprehensive understanding of covert attention dynamics

Moreover, the ability to non-invasively track attention physiologically could also support the use of these methods beyond attention research, but also in clinical and practical applications, such as the diagnosis of spatial attention disorders (e.g., spatial neglects). Open-DPSM is particularly promising for diagnosing visuo-attentional deficits by mapping pupil responsivity across different areas of space, which can indicate issues like visual field defects and hemispatial neglect (Portengen et al., 2021; Ten Brink et al., 2023). This is particularly relevant as it could facilitate assessment in patients with low attentional resources, such as after brain damage or in children and elderly, by using complex and dynamic stimuli that are more engaging and easier to assess. For instance, using pupillometry, researchers could measure attentional bias in participants with left-sided neglect, finding pupil light responses would disproportionately reflect the brightness on the right side (Ten Brink et al., 2023). This study further supports the ability to use a pupillometry based method to offer physiological measure of (covert) attention, without requiring behavioral responses.

Conclusion

In summary, the findings of this study support the effectiveness of using pupil size changes to measure covert attention, while also highlighting the efficacy of the Open-DPSM toolkit in identifying both exogenous and endogenous covert attention to dynamic and complex stimuli. These findings reinforce that pupil size changes can reflect both exogenous attention driven by strong visual stimuli and endogenous attention driven by voluntary goals, offering insights into attentional mechanisms. Future research should continue to explore the applications of the Open-DPSM toolkit in various contexts and further validate its effectiveness in capturing attentional shifts across different types of stimuli and tasks.

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Appendix

Condition Instructions

Condition	Instruction
Left	Pay attention to the moving circle on LEFT. Press [space] when circle on LEFT stops. Press [b] to begin.
Right	Pay attention to the moving circle on BOTH SIDES. Press [space] when circle on RIGHT stops. Press [b] to begin.
Both	Pay attention to the moving circle on BOTH SIDES. Press [space] when circle on BOTH SIDES stop. Press [b] to begin.
None	Look CENTER and enjoy. Press [b] to begin.

Note. Condition instructions were displayed in white text on a black background.