Covert shifts of attention towards the visual periphery induce pupil dilation

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Abstract

Previous studies have suggested that pupil size increases with covert shifts of attention to the peripheral as compared to the (para)foveal visual field, i.e., with increasing "attentional breadth". This finding is crucial because it matches the theoretical prediction that (para)foveal vision benefits more from the visual acuity provided by small pupils than peripheral vision does. However, no study has investigated this question while controlling for all possible confounds (e.g., task difficulty). Throughout three experiments (N=100) we tested whether pupil size increases with increasing attentional breadth, and if this effect depends on the 'shape' of attention, that is, whether attention is broadly (Annulus Attention) or narrowly (Spotlight Attention) distributed. We found that pupil size increases with covert shifts of attention to the peripheral visual field, i.e., increasing attentional breadth, with no clear difference between the two 'shapes' of attention. We further found a correlation with performance, suggesting a functional benefit of the link between attentional breadth and pupil size. Finally, we propose that cognitively driven pupil dilation is not merely a convenient marker of activity in brain areas such as the Locus Coeruleus, but rather is an adaptive response that reflects an emphasis on peripheral vision over foveal vision.

Introduction

Spatial attention is commonly seen as a spotlight that highlights a certain region in space and thus enhances processing for that region. Importantly, the size of this spotlight is not constant, but adapts to the demands of the situation (Eriksen & St. James, 1986; Greenwood & Parasuraman, 1999, 2004; Lawrence et al., 2020; Müller et al., 2003). For example, when trying to find a certain figure in a book, your attention is broadly distributed as you are flipping through the pages. Yet, once you have found the figure, your attention narrows and focuses on the details of the figure and the caption underneath. The zoom-lens theory of attention was developed to accommodate the fact that the focus of spatial attention not only has a location but also a size (Eriksen & St. James, 1986; Eriksen & Yeh, 1985; LaBerge, 1983). Attentional breadth refers to the size of this zoom lens, which gets bigger when attention is diffusely spread across the visual field, thus also encompassing peripheral vision, and smaller when attention is focused centrally, encompassing only (para)foveal vision (Brocher et al., 2018; Mathôt, 2020).

The zoom-lens theory postulates an inverse relationship between the breadth of attention and visual processing quality; in other words, broadly distributed attention results in parallel but superficial processing of stimuli, while narrowly distributed attention allows for detailed scrutiny of stimuli. Referring back to the example from the beginning, broadly distributed attention allows us to quickly scan the pages until we find the right figure, based on a general impression of what this figure should look like, but at the expense of fine resolution for the text presented on those pages. Conversely, narrowly distributed attention provides us with sharp and detailed information about the attended location, but at the expense of sensitivity for things appearing in the periphery.

These functional differences in processing quality between broadly and narrowly focused attention map onto physiological differences between foveal and peripheral vision at the level of the retina. Firstly, photoreceptors are not uniformly distributed across the retina: the density of cones is highest near the fovea, and declines toward the periphery (Hirsch & Curcio, 1989; Pumphrey, 1948; Rosenholtz, 2016). Furthermore, in the fovea, photoreceptors have one-to-one connections to ganglion cells, which enables photoreceptors' input to be transmitted with minimal loss of spatial information. In contrast, in the peripheral retina, many photoreceptors (both rods and cones) project to a single shared ganglion cell, thus losing spatial information. Because of these physiological properties of the retina, foveal vision provides higher visual acuity than peripheral vision does (Wolfe et al., 2009; Curcio et al., 1987).

The difference in sensitivity between peripheral and foveal vision also has implications for the optimal size of the pupil. When the pupil is constricted, only a small part of the lens is exposed, thus lessening optical distortions (both spherical and chromatic) that cause optical blur (Mathôt, 2018; Wang & Ciuffreda, 2006), in turn resulting in high visual acuity. In contrast, when the pupil is dilated, a larger part of the lens is exposed, thus allowing more light to enter the eye, in turn resulting in increased visual sensitivity. The size of the pupil therefore reflects a trade-off between visual acuity and sensitivity, where small pupils favor acuity over sensitivity. Crucially, due to the physiology of the retina, high visual acuity (and thus a small pupil) is mainly beneficial for foveal vision, whereas it is largely wasted on peripheral vision.

The notion that large pupils are beneficial for peripheral vision has empirical support from a study by Mathôt & Ivanov (2019) who manipulated pupil size while measuring performance on detection and discrimination tasks. They found that detection of faint stimuli in peripheral vision is better with large pupils, whereas discrimination of fine-grained stimuli in

foveal vision is better with small pupils. However, in this study, pupil size was manipulated, thus leaving open the question of whether our pupils also automatically adapt their size to the situation. More specifically, does pupil size increase with increasing attentional breadth?

This question has been addressed already in a number of studies (Brocher et al., 2018; Daniels et al., 2012; Klatt et al., 2021; Kolnes et al., 2022); for example, in a series of experiments conducted by Brocher and colleagues (2018; Klatt et al., 2021), participants were exposed to a varying number of target stimuli presented laterally at various levels of eccentricity (12.5°, 27.5°, and 42.5°) relative to a central fixation dot. Prior to the presentation of the targets, participants received a cue that informed them of the eccentricity of the upcoming targets; this served as a manipulation of attentional breadth. Finally, participants reported the number of targets on each side of the display. The results showed that pupil size increased with increasing attentional breadth. However, task performance was poorer at the far- (42.5°) and medium-eccentricity (27.5°) conditions as compared to the near-eccentricity condition (12.5°); this makes it impossible to disentangle whether the increase in pupil size with increasing attentional breadth simply originated from greater mental effort (because the task was more difficult for the medium and far eccentricities), or from attentional breadth per se. Daniels and colleagues (2012) tested the same hypothesis in a set of experiments in which participants were presented with stimuli in a diamond-like configuration; stimuli were displayed centrally and/or peripherally. Participants covertly attended either to the central (narrow attention) or peripheral (broad attention) stimuli based on a cue. For example, in one experiment, the luminance of a central dot changed on a trial-by-trial basis, indicating narrow or broad attention. Even though their results suggested that pupil size increased with increasing attentional breadth, it was not mentioned if the cues were counterbalanced, which is important in order to disentangle the effect

of visual stimulation on pupil responses from the effect of attentional breadth per se. Finally, in a very recent study, Kolnes and colleagues (2022) manipulated attentional breadth by cueing participants' attention either to a small or a large circular rim at different eccentricities (near and far), and asked them to remember the location of a gap in the cued rim. Following this task, a visual search task was used to behaviorally assess the manipulation of attentional breadth; the task consisted of stimuli spread over various eccentricities, and participants searched for a target stimulus that was oriented differently from the other stimuli. Consistent with the above-mentioned studies, they found that pupil size increased with increasing attentional breadth (i.e., when the large rim was cued). Even though Kolnes and colleagues (2022) aimed to carefully control for common confounds (visual input and gaze position), it remained unclear if auditory cues, used to induce different levels of attentional breadth, were counterbalanced; again this is crucial because not only visual, but also auditory, stimuli have an effect on the pupil (Gingras et al., 2015). In addition, task difficulty was not controlled between conditions, although in this case the task was easier for the far eccentricity than for the near eccentricity (i.e., opposite to the paradigm used by Brocher et al., 2018; Klatt et al. 2021).

Taken together, several studies have provided preliminary evidence for the effect of attentional breadth on pupil size, such that pupil size increases with increasing attentional breadth; however, none of these studies simultaneously controlled for all potential confounds. Therefore, in the current study, we tested the same prediction while carefully controlling for all potential confounds. We believe that this is crucial because of the theoretical importance of the relationship between attentional breadth and pupil size. In addition, we tested whether the effect of attentional breadth on pupil size depends on the 'shape' of attention, that is, whether attention is distributed broadly or focused on specific locations at various eccentricities. Finally, we

explored the relationship between attentional breadth, pupil size, and behavioral performance, which is important to better understand the role of pupil size in behavior.

Results

To investigate the effect of attentional breadth on pupil size, we analyzed eye-tracking data from 100 participants performing a visual discrimination task. We conducted three separate experiments, which are described in detail under Materials and methods and analyzed separately as described in the Appendix; however, because the results of all three experiments were very similar, we will focus on the combined data below. Participants saw three concentric annuli that occupied various eccentricities (near [1.16°], medium [3.47°], and far [10.40°]). Next, after an interval of at least 2000 ms, a target appeared within one of the annuli; the target was either a slight increment or decrement of luminance relative to the background, and participants reported its identity (luminance increment or decrement). To avoid differences in task difficulty between eccentricities, we used an interleaved staircase procedure to keep accuracy constant across eccentricities by varying the visibility of the target. Crucially, 1000 ms before the presentation of the annuli, we cued participants' covert attention by indicating either the annulus (Annulus Attention) or the specific location within the annulus (Spotlight Attention) where the upcoming target would most likely (but not always) appear (see Figure 1a). Participants were required to keep their gaze fixated in the middle of the screen throughout the trial.

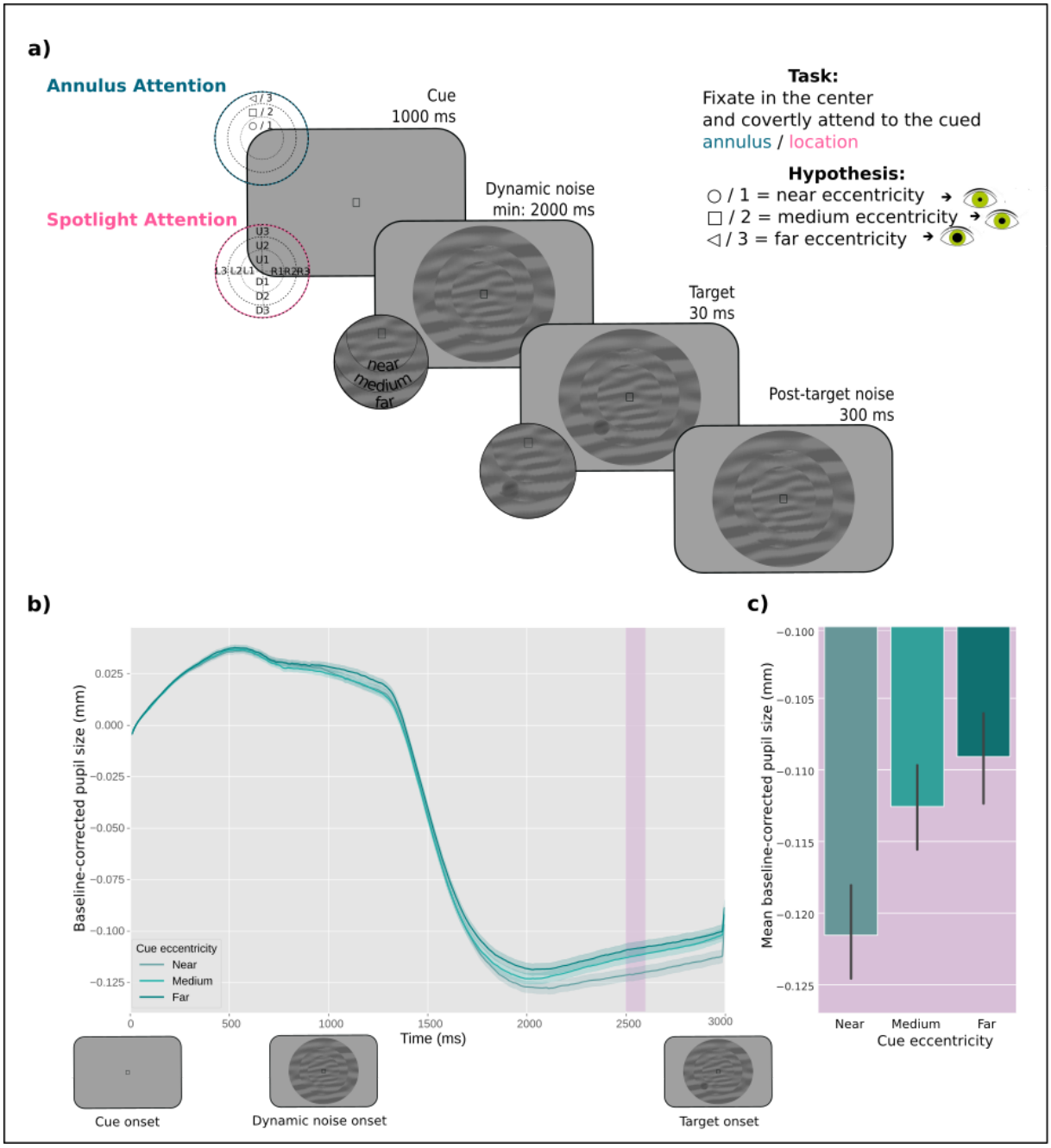

Figure 1. a) Schematic trial sequence. In the Annulus Attention condition, participants' attention was cued to one of the annuli at different eccentricities. In the Spotlight Attention condition, participants' attention was cued to a specific location within one of the annuli. Participants reported whether a target was a luminance increment or, as in this example, a luminance decrement embedded in a dynamic stream of noise. *b)* The effect of attentional breadth on pupil size. The y-axis represents baseline-corrected pupil size in millimeters. The x-axis represents time in milliseconds since cue onset. The panels below the x-axis represent the order of the events in experiments. Differently colored lines represent the three cue eccentricities (near,

medium, far) corresponding to different levels of attentional breadth. The pink-shaded area represents the time window (2500-2600ms) where the effect was the strongest, as determined through a cross-validation procedure. Error bands indicate the grand standard error. *c)* Mean baseline-corrected pupil size in millimeters as a function of cue eccentricity within the selected time window (2500-2600ms).

The effect of attentional breadth on pupil size

We ran a four-fold cross-validation analysis on a predetermined time-window of 750-3000 ms after the onset of the cue to assess differences in pupil size across eccentricities. This procedure is described in more detail in Mathôt and Vilotijević (2022); however, in brief, this analysis determines a time point at which an effect of interest (Cue Eccentricity in our case) is strongest by splitting the data into training and test sets. Next, for each test set, the corresponding training set is used to determine the time point at which the effect is the strongest; a single linear mixed effects (LME) analysis is then conducted for the full dataset, using for each test set the time point that was selected based on the corresponding training set, thus avoiding both circularity and the need to correct for multiple comparisons. This means that the dependent variable consists of a column of (baseline-corrected) pupil-size values that correspond to different samples for different trials.

Our model included pupil size as dependent variable, Cue Eccentricity as fixed effect (coded ordinally: -1 = *near*, 0 = *medium*, 1 = *far*; this was the case for subsequent analyses as well), and by-participant random intercepts and slopes. The lower boundary of our period of interest (750 ms) was decided on the basis of the finding that a voluntary shift of covert visual attention towards a bright or dark surface affected pupil size from about 750 ms after cue onset (Mathôt et al., 2013). The upper boundary (3000 ms) was set to the first moment at which the target could appear in any of the three experiments. The effect of Cue Eccentricity on pupil size

emerged around 1750 ms after cue onset and the cross-validation analysis showed that it reached maximum around 2500 and 2600 ms after cue onset (t = 2.75, p = .006). Specifically, and in line with our hypothesis, we found that the pupil size increased with increasing attentional breadth (see Figure 1b, c).

Next, to test whether the effect of attentional breadth differed between the Annulus Attention and Spotlight Attention conditions, we focused on mean pupil size during the 2500-2600 ms window as selected by the cross-validation analysis. We conducted an LME analysis with mean pupil size during the selected interval as dependent variable, Cue Eccentricity and Attention Shape (reference: Annulus Attention) as fixed effects, and by-participant random intercepts (a model with by-participant random slopes failed to converge). This revealed, as before, a main effect of Cue Eccentricity (b = 0.008, SE = 0.003, t = 2.77, p = .006), but no main effect of Attention Shape (b = 0.008, SE = 0.005, t = 1.58, p = .115), and—more importantly—no interaction between Cue Eccentricity and Attention Shape (b = -0.003, SE = 0.004, t = 0.74, p = .457).

Taken together, we found an effect of attentional breadth on pupil size, but this effect did not reliably depend on the 'shape' of attention (Annulus vs Spotlight).

Behavioral cueing effect

Next, to test the behavioral cueing effect, we ran Generalized Linear Mixed Models (GLMM) testing a model that included Accuracy as dependent variable, Cue Validity as fixed effect, and by-participant random intercepts and slopes for Cue Validity. The results showed a behavioral cueing effect; that is, participants were more accurate on valid versus invalid trials (b = 0.17, SE = 0.03, z = 5.02, p < .001; Figure 2).

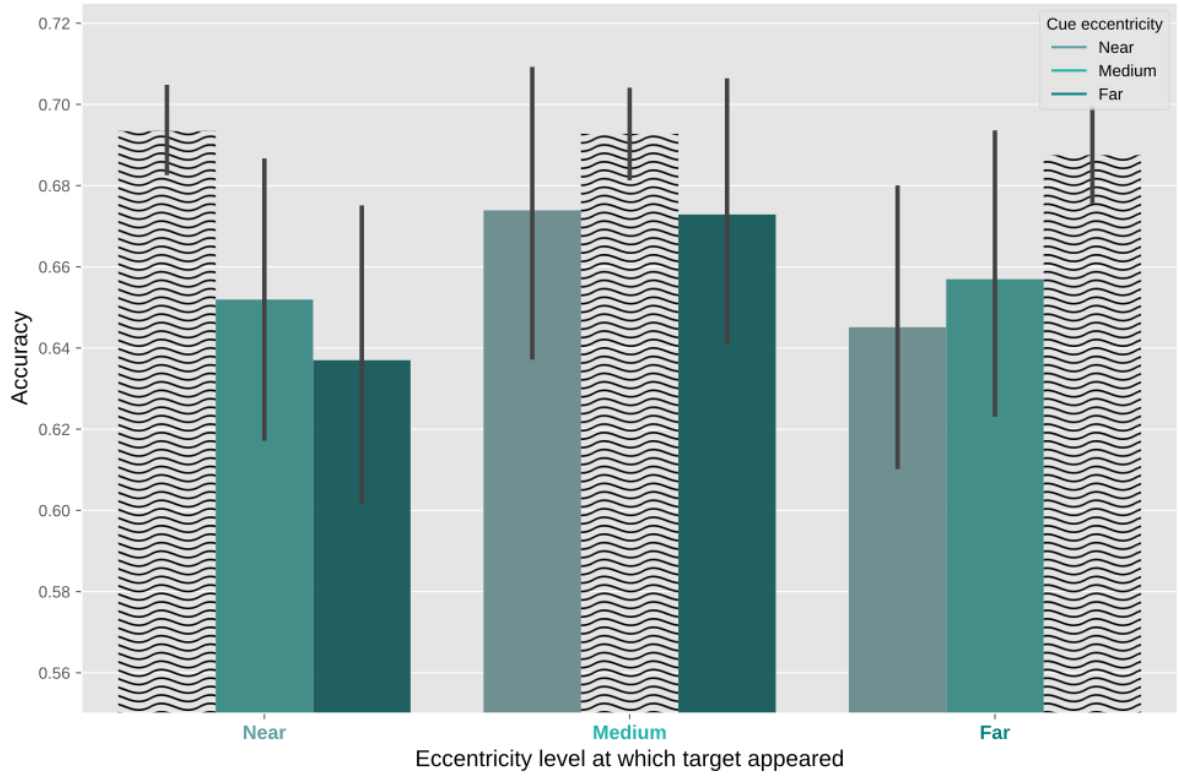

Figure 2. Behavioral results. Accuracy as a function of the eccentricity at which the target appeared (*x*-axis) and the eccentricity that was cued (bars). Shaded wavy bars represent valid conditions. Error bars represent the grand standard error.

Correlations between pupil size and behavior

Figure 3a depicts individual differences across participants in the strength of the effect of attentional breadth on pupil size; here, the "Attentional Breadth" effect corresponds to the Pearson correlation coefficient between Cue Eccentricity and mean pupil size during the 2500-2600 ms window, determined for each participant separately. About two-thirds of the participants showed an effect in the hypothesized direction; in other words, although the effect of attentional breadth is highly reliable at the group level, there is a lot of interindividual variability.

Next, we assessed how the attentional-breadth effect relates to visual sensitivity (Figure 3c); here, sensitivity corresponds to 1 - Target Opacity, because the staircase procedure

converged on a low target opacity for participants who performed well. We found a significant negative correlation between the attentional-breath effect size and Target Opacity. In other words, participants who exhibited a stronger effect of attentional breadth on pupil size were better able to detect targets whose opacity was low (higher task difficulty). However, this was only true for the Annulus Attention condition (r = -0.27, p = .020), and not for the Spotlight Attention condition (r = .01, p = .957). These two correlations differed significantly (z = -1.99, p = .023).

We also assessed how the attentional-breadth effect relates to the behavioral cueing effect (Figure 3b); here, the cueing effect is calculated as the accuracy on valid trials minus the accuracy on invalid trials, determined for each participant separately. Strikingly—and unexpectedly—the attentional breadth was negatively correlated with the behavioral cueing effect. In other words, participants who exhibited a stronger attentional-breadth effect exhibited a *weaker* behavioral cueing effect. However, this was only true for the Annulus Attention condition (r = -.30, p = .011), and not for the Spotlight Attention condition (r = .11, p = .380). (We will return to this in the Discussion.)

Finally, performance does not relate to the behavioral cueing effect (r = -.00, p = .976); that is, there is no systematic relationship between how well participants perform the task, and how strongly they show a behavioral cueing effect (Figure 3d).

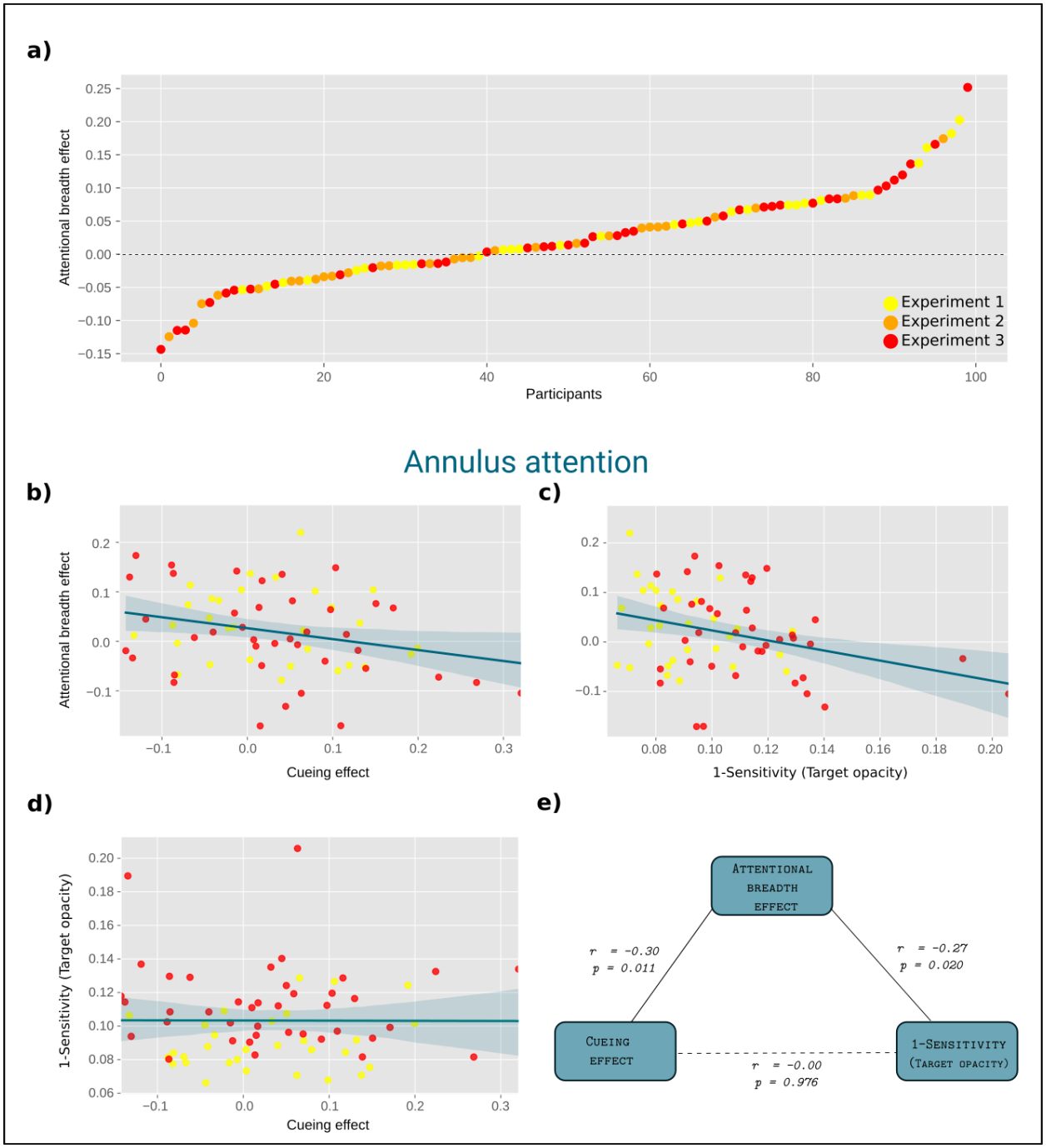

Figure 3. a) Attentional-breadth effect sizes for individual participants sorted by effect size. *b)* Correlation between attentional-breadth effect size and behavioral cueing effect. *c)* Correlation between attentional-breadth effect size and inverse sensitivity measure (target opacity). *d)* Correlation between inverse sensitivity and cueing effect. *e)* Schematic illustration of the link between attentional breadth effect, cueing effect, and inverse sensitivity with corresponding correlations. *Note:* Detection of targets with lower opacities meant higher sensitivity.

Discussion

We have reported three experiments that investigated whether pupil size increases with increasing attentional breadth, and if this effect depends on the 'shape' of attention, that is, whether attention is distributed broadly (Annulus Attention) or narrowly (Spotlight Attention). Large pupils are known to benefit detection of faint stimuli in peripheral vision (Mathôt, 2020; Wang et al., 2021; Woodhouse, 1975); therefore, the question of whether pupils reflexively dilate in response to increased attentional breadth is crucial for a better understanding of pupil responses as a form of 'sensory tuning': a subtle adjustment of the eyes to optimize visual information intake for a given situation (Mathôt, 2020).

To test this, participants had to discriminate the luminance of a target that was presented within one of the annuli that occupied various eccentricities (Figure 1a). We cued participants' covert attention to either the annulus (Annulus Attention condition) or the specific location within the annulus (Spotlight Attention condition) where the upcoming target would most likely (but not always) appear. We measured pupil size in anticipation of the target. In doing so, we made sure that task difficulty, gaze position, and visual input (including luminance and contrast)—factors that are known to influence pupil size—were kept constant across conditions, which was a crucial improvement over previous studies that addressed this question (Brocher et al., 2018; Daniels et al., 2012; Klatt et al., 2021; Kolnes et al., 2022).

We found that pupil size increases with increasing covert shifts of attention to the peripheral visual field, i.e., attentional breadth. As shown in Figure 1b, the pupil slightly dilates during the cue presentation (1000 ms) after which it rapidly constricts once dynamic noisy annuli are shown; this constriction reflects the typical pupillary response to heavy visual stimulation (such as dynamic noise) and thus is consistent across conditions. Next and most importantly,

pupil traces begin to differ between conditions around 1750 ms after the cue onset, reaching a maximum difference around 2500-2600 ms, and lingering until the target's presentation. This means that when the target was expected to appear at the near level of attentional breadth (encompassing central vision), pupils were smaller than when the target was expected at the far or medium levels of attentional breadth (encompassing peripheral vision). Additionally, our data demonstrate that this effect does not depend on the shape of attention: Annulus Attention or Spotlight Attention.

We further found that, between participants, sensitivity was reliably correlated with the effect of attentional breadth on pupil size, at least in the Annulus Attention condition (Figure 3c); that is, those participants whose pupils dilated strongly when attention was directed to the periphery were the same participants who performed well on the task. This supports the notion that tuning pupils to best serve peripheral and central vision enhances overall sensitivity, suggesting a functional benefit of attentional breadth.

Surprisingly, the behavioral cueing effect was negatively correlated with the effect of attentional breadth on pupil size (Figure 3b); that is, those participants whose pupil size was strongly affected by the cue were the same participants whose behavior was weakly affected by the cue. Possibly, this seemingly paradoxical pattern of results is an artifact of the task that we used in the current study. Specifically, participants needed to distinguish a subtle luminance increment from a decrement, which is a task that relies more on visual sensitivity than on acuity *also* when stimuli are presented in (para)foveal vision. To understand how this can result in a negative correlation between the behavioral cuing effect and the effect of attentional breadth on pupil size, imagine a participant who shows a strong attentional breadth effect, that is, a participant whose pupils constrict strongly when the near annulus is cued. Across the board, this

participant will perform relatively poorly when the near annulus is cued (because of the small pupils), even when the cue is valid and the target actually appears in the near annulus. Conversely, this participant will perform relatively well when the far or medium annulus is cued (because of larger pupils), even when the cue is invalid and the target actually appears in the near annulus. Because of this, the attentional breadth effect may, in our task, counteract the behavioral cuing effect. In turn, this may have resulted in a negative correlation between both effects. Importantly, in real-life—and in contrast to our experiment—tasks that people perform with (para)foveal vision, such as reading, generally emphasize visual acuity over sensitivity, whereas tasks that people perform with peripheral vision, such as detecting unexpected movement, generally emphasize visual sensitivity over acuity. An important avenue for future research will be to use laboratory tasks that more closely mimic how people use (para)foveal and peripheral vision in real life, and to investigate the functional role of the relationship between attentional breadth and pupil size in such tasks.

Although this was not the primary focus of our study, our behavioral results also speak to the question of whether attention can be shaped as a 'doughnut', that is, whether participants were able to attend to the outermost annulus in our stimulus display without also attending to the medium and innermost annuli. Specifically, we found that attention was *selective* for the cued annulus (Nobre & Kastner, 2014), as participants were consistently better performing on validly cued trials across *all* eccentricities (Figure 2). This suggests that attention was deployed in the shape of differently sized annuli rather than differently sized filled circles. This is noteworthy because it implies an important difference between the concepts of attentional breadth and zoom-lens theory; the latter assumes attentional deployment in a form of differently sized filled circles (this also matches the concept of "attentional scaling" proposed by Lawrence et al.,

2020), whereas attentional breadth assumes that attention is deployed in the form of differently sized annuli (Jefferies & Di Lollo, 2015; this also matches the concept of "doughnut" attention; Muller & Hubner, 2002). Our results suggest that attention can be distributed in the shape of a doughnut.

Our results have important implications for the Adaptive Gain Theory (AGT; Aston-Jones & Cohen, 2005). This theory differentiates between two modes of behavior—*exploitation* and *exploration*—and relates them to locus coeruleus (LC) activity and task utility (i.e. how rewarding it is to perform a certain task). Specifically, information about task utility would be sent from higher-order brain structures (anterior cingulate cortex, orbitofrontal cortex) to LC, driving two modes of LC activity: phasic and tonic (Aston-Jones & Cohen, 2005; Usher et al., 1999). Phasic activity would reflect on-task behavior (exploitation), while tonic activity would reflect disengagement from the current task and seeking other tasks (exploration). Crucially, pupil size correlates with LC activity, and is therefore often used as a non-invasive measure of the extent to which people are in an exploration mode of behavior (large pupils) versus an exploitation mode of behavior (medium-to-small pupils) (Brink et al., 2016; Gilzenrat et al., 2010; Jepma & Nieuwenhuis, 2011). Our results add to this theory by offering a functional explanation for *why* there is a correlation between pupil size and modes of behavior. Specifically, an exploration mode of behavior is likely characterized by an emphasis on peripheral vision, and through this route may lead to pupil dilation. The same logic applies to other situations that are associated with pupil dilation. For example, high arousal is associated with pupil dilation (and thus high LC tonic activity mode; Binda & Murray, 2015; Bradley et al., 2008); thus far, arousal-related pupil dilation has been interpreted as an epiphenomenal physiological response. However, we propose that arousal-related pupil dilation is a way in

which the visual system tunes itself to best serve the demands of the situation; specifically in a situation that elicits high arousal (e.g., when you are afraid) it is crucial to be able to detect things anywhere in the visual field with little concern about their details; thus, the visual system recognizes that detection is more important than discrimination, and pupils consequently dilate to provide greater sensitivity.

In sum, we demonstrate that pupil size increases with covert shifts of attention to the peripheral visual field, that is, with increasing attentional breadth, with no clear difference between how attention is distributed. We further found that participants who showed a large attentional-breadth effect on pupil size also performed better on the task, at least for the Annulus Attention condition, suggesting a functional benefit of the link between attentional breadth and pupil size. Finally, we propose that, more generally, cognitively driven pupil dilation reflects an emphasis on peripheral vision over foveal vision, and that this may explain why the pupil dilates in response to increased arousal or a switch to an exploration mode of behavior as postulated by the AGT.

Materials and methods

General

We conducted three experiments in order to test whether pupil size increases with increased attentional breadth. Each experiment's methods, hypotheses, data sampling and analysis plans were preregistered on the Open Science Framework. All data, analysis scripts, and supplementary materials are available at https://osf.io/4nrgb/. The experiments were approved by the Ethics review board of the Department of Psychology at the University of Groningen (study approval code: PSY-2122-S-0139).

Participants

In total, 111 (N_{exp1} = 30; N_{exp2} = 32; N_{exp3} = 49) first-year psychology students from the University of Groningen gave informed consent to participate in the study for course credits. For each experiment, we determined a target sample size and data exclusion criteria beforehand; we aimed for a target sample size of 30 participants for Experiment 1, and the same sample size was estimated for Experiment 2 based on a bootstrap power analysis conducted on the data from the first experiment (power = .81). Since we wanted to investigate an interaction effect in Experiment 3, and since we did not have a reliable effect-size estimate for a power analysis, we aimed for a target sample size of 40 participants. Prerequisites for retention of participant's data were: 1) full completion of the experiment, 2) efficacy of the staircase procedure (see Data Exclusion). All participants had normal or corrected-to-normal vision. All participants were unique for each experiment.

Apparatus and data acquisition

The experiments were programmed in OpenSesame (Mathôt et al., 2012) using PyGaze for eye tracking (Dalmaijer et al., 2014). Stimuli were presented on a 27-inch monitor (1920 × 1080 pixels resolution) and an Eyelink 1000 (sampling frequency of 1000 Hz; SR Research Ltd., Mississauga, Ontario, Canada), was used for eye tracking. Participants' right eyes were recorded. All experiments were conducted in a dimly lit room.

Procedure

Prior to the start of the experiment, the participant was well seated at about 60 cm distance from the computer monitor, with his or her chin placed on a chin-rest to keep the head in a stable position. First, a calibration-validation procedure was run. Before each trial, 1-point eye-tracker recalibration ("drift-correction") was performed.

Throughout the experiments, participants were instructed to maintain their focus in the center of the display marked by a fixation dot. Each trial started with a centrally presented cue for 1000 ms that indicated at which level of eccentricity a target was most likely to appear. The cue display was followed by the dynamic noise display that consisted of concentric annuli that differed in their respective radii, occupying different eccentricities: near (1.16°), medium (3.47°), and far (10.40°). The annuli were filled with dynamic, oriented noise patches that changed every 30 Hz. The spatial frequency of the noise patches decreased with eccentricity, following the formula for cortical magnification as determined by Carrasco & Frieder (1997) for the upper visual field. At a random moment within the last second[1] of the dynamic noise presentation, the target (a subtle luminance increment or decrement) was briefly flashed for 30

[1] The exact time window in which the target appeared was 2000-3000ms (in Experiment 1) while the duration of the dynamic noise display was a bit prolonged in Experiments 2 and 3, so the target appeared within the time-window of 2500-3500ms after the dynamic noise onset.

ms, after which the dynamic noise continued for another 300 ms. On a majority of trials (80%) the target appeared at the cued annulus or location (valid trials) while on the remaining 20% it appeared at a non-cued annulus or location (invalid trials). Participants' task was to covertly attend to the target and report whether the target was a luminance increment or decrement by pressing the left or right arrow on the keyboard, respectively. The sole difference between Experiment 1 and 2 was the type of the cue that was used, indicating the shape of attention (Annulus or Spotlight). Specifically, in Experiment 1 we cued only the annulus (near, medium, or far) where the target was most likely to appear. To do so, we presented participants with symbolic cues (□, ○, ◁) that were indicative of each annulus. The mapping between cue symbol and eccentricity was counterbalanced across participants to ensure completely identical visual input in all conditions across participants. However, in Experiment 2, we cued both the annulus (near, medium, or far) and the location within the cued annulus (upper, lower, left, or right). Here, the cues were presented as a combination of codes for annuli (1/2/3 for near/medium/far) and codes for locations (U/D/R/L for up/down/right/left): for example, if U2 was presented that meant that the target was most likely to appear at the upper location of the middle annulus. This mapping was constant across all participants, because otherwise the task would be too complicated. Experiment 3 combined both cueing approaches (hence, both attentional shape forms) in a blocked design, keeping the same cues as in Experiment 2 for the Spotlight condition, where a specific location within a specific annulus was cued (Spotlight Attention Condition), and using only numeric cues (1,2,3) for the condition where only an annulus was cued (Annulus Attention Condition). All cues were the same size (.69°) and colored in black. All stimuli were superimposed on a gray background.

To ensure that the accuracy on validly cued trials was maintained at approximately 70%, we implemented a 3-up-1-down staircase procedure[2] (Leek, 2001), separately for each eccentricity, varying the opacity of the target with 1% steps. In case three correct responses were given in a row, the target opacity would be decreased by 1%, thus increasing task difficulty, while in case of a single incorrect response, the target opacity would be increased by 1%, thus decreasing task difficulty. Throughout the experiment, participants received feedback in the form of a black checkmark (.92°) or x mark (.92°), indicating correct and incorrect responses, respectively.

All experiments consisted of 330 trials that were shuffled and divided into 10 blocks. Experiment 1[3] and 2 consisted of 90 practice trials and 240 experimental trials. Experiment 3 consisted of 30 practice trials and 300 experimental trials, half of which represented Spotlight Attention condition (5 successive blocks) and the other half represented Annulus Attention condition. The order of blocks was counterbalanced across participants.

Data exclusion

Before analyzing the data, we checked if the staircase procedure was effective in keeping task difficulty equal across eccentricities. To that aim, after collecting the target sample size for each experiment, we compared participants' performance when different eccentricities were cued by conducting Bayesian repeated measures ANOVA (with default parameters of JASP (JASP Team, 2022)) only on validly cued trials with Accuracy as dependent variable and Cue Eccentricity as independent variable. We used a Bayes Factor ($BF_{01} > 3$ as a threshold for finding

[2] In Experiment 1 staircase was set to 2-up-1-down.

[3] During practice trials, participants were shown both the cue in symbolic (□, ○, ◁) and written ('near','medium','far') form to make sure that they learned the mapping. Between the blocks, participants were asked to verbally repeat to the experimenter which symbol corresponds to which annulus, in order to verify that participants remembered the cue-annulus mapping.

substantial evidence in favor of the null hypothesis. This condition was not met in Experiment 3 (initial BF_{01} = 2.25), so we determined for each participant separately absolute performance deviance (this step was also preregistered), i.e., how much performance differed across eccentricities based on the following formula:

`|Accuracy(near)-Accuracy(overall)| + |Accuracy(medium)-Accuracy(overall)| +|Accuracy(near)-Accuracy(overall)|`. Next, we iteratively excluded 9 participants with the largest absolute performance deviance until we found substantial evidence for the null hypothesis. Finally, we recruited additional participants to reach again the target sample size, after which we ended up with BF_{01} = 3.63. In Experiment 2, the staircase procedure did not work for one participant ($M_{accuracy}$ = .44) while one other participant made a large number of eye movements ($GazeError_{max}$ = 19.07°). After these participants were replaced, we ended up with BF_{01} = 3.15. This condition was immediately met in Experiment 1 (BF_{01} = 6.29). Overall, the data from 100 participants was further analyzed (N_{exp1} = 30; N_{exp2} = 30; N_{exp3} = 40).

Pupillary data: preprocessing

Following the workflow for preprocessing pupillary data that we described elsewhere (Mathôt & Vilotijević, 2022), we first interpolated blinks and downsampled the data by a factor of 10. Also, we converted pupil size measurements from arbitrary units to millimeters of diameter by using the formula specific to our lab (Wilschut & Mathôt, 2022). Next, we baseline-corrected the data by subtracting the mean pupil size during the first 50 ms after the onset of the cue (baseline period) from all subsequent pupil-size measurements on a trial-by-trial basis. Trials containing baseline pupil sizes of ± 2 *z*-scores were considered outliers, and hence excluded from the data. Missing trials (due to technical issues with recording in Experiment 2

and 3) were excluded as well (0.05%). In total, 1576 trials (Total = 5.91%; Exp1 = 5.58%, Exp2 = 5.44%, Exp3 = 6.51%) were excluded from the data.

Additional information

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Appendix

To test the attentional breadth effect in each experiment separately, we run LME with Mean Pupil Size during the selected time window (2500-2600 ms), determined by cross-validation analysis run on the collapsed data, as a dependent measure while Cue Eccentricity (ordinal: -1 = *near*, 0 = *medium*, 1 = *far*) was a fixed effect and by-participant random intercepts and slopes. Additionally, we tested cueing effect by conducting GLMM using Accuracy as the dependent variable while Cue Validity was included as a fixed effect. The random-effect structure included a by-subjects random intercept and random slopes for Cue Validity.

Experiment 1 - Annulus Attention. The main effect of Cue Eccentricity was significant, $b = 0.012$, $SE = 0.005$, $t = 2.696$, $p = 0.007$. Looking at the behavioral performance, we observed a cueing effect suggesting that participants were more accurate on valid trials, ($b = 0.14$, $SE = 0.05$, $z = 2.61$, $p = 0.009$).

Experiment 2 - Spotlight Attention. When a specific location within a certain annulus was cued the pupillary effect did not reach significance ($b = 0.004$, $SE = 0.004$, $t = 1.05$, $p = 0.315$), although the pattern of results was still in line with overall results. The cueing effect was now even more prominent, $b = 0.25$, $SE = 0.05$, $z = 4.63$, $p = 0.000$.

Experiment 3 - Annulus Attention and Spotlight Attention. The pupillary results were again in the hypothesized order, however, the results did not reach overall significance (b = 0.004, SE = 0.004, t = 1.21, p = 0.262). When analyzing conditions─Annulus Attention and Spotlight Attention─separately, the pupillary results were in the hypothesized order, however, none of them reached significance: Annulus Attention condition: b = 0.001, SE = 0.005, t = 0.23, p = 0.821; Spotlight Attention condition: b = 0.007, SE = 0.005, t = 1.45, p = 0.147. As regards the cueing effect, we observed the overall cueing effect in Experiment 3, b = 0.20, SE = 0.05, z = 4.31, p = 0.000). This was also true when only Spotlight Attention condition was tested (b = 0.23, SE = 0.07, z = 3.42, p = 0.001) as well as for Annulus Attention condition (b = 0.18, SE = 0.07, z = 2.67, p = 0.008).

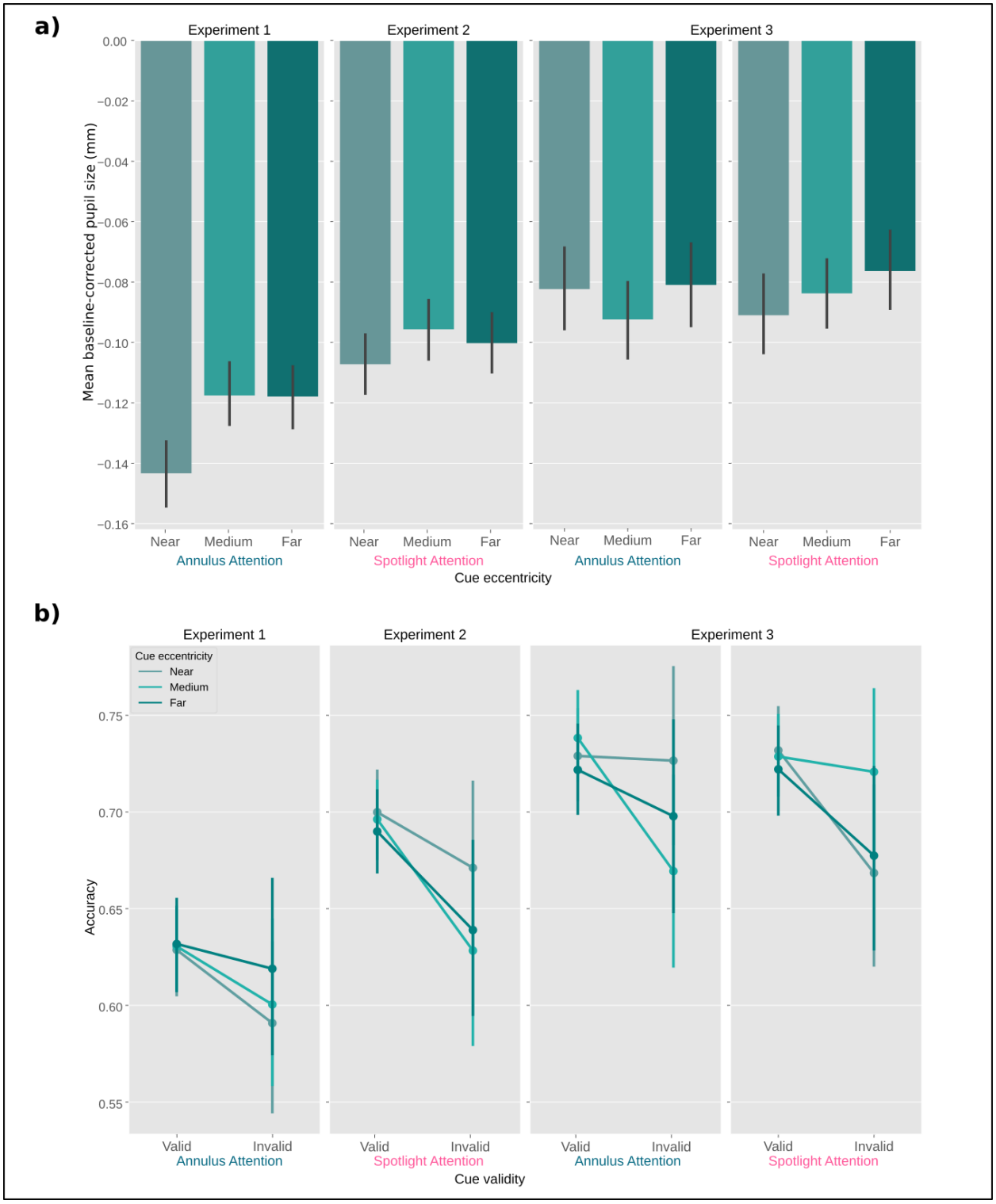

Figure 4. *a)* Mean baseline-corrected pupil size expressed in millimeters as a function of cue eccentricity across experiments. *b)*. Accuracy as a function of cue validity across experiments and corresponding conditions. Error bars indicate 95% confidence interval.