Attentional Modulation of the Pupillary Light Response to Gaze Cueing of Covert Attention

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Abstract

This paper explores whether a pupillary light response can be induced by gaze cueing. The conducted experiment was designed to draw the covert attention of participants towards a dark or bright stimulus, by means of exogenous and gaze cueing. Differences in pupil size between attending dark and attending bright indicate attentional modulation of the pupillary light response. The utilized eye-tracker and recorded responses allowed for pupillary and behavioural (accuracy, response times) analysis. In line with earlier findings it is hypothesized that the pupillary light response to gaze cueing shows attentional modulation. The results show no significant differences between attending bright or dark in the gaze cue condition. The pupillary light response in the exogenous cue condition was replicated, but no inhibition of return was visible in the behavioural or pupillary data. Because the known correlation between behaviour and pupil was not replicated, it is concluded the experimental design needs alterations. Ultimately, possible alterations are discussed.

Introduction

Human eyes can readily adapt to changes in luminance; depending on the amount of available light the size of the pupil varies to accommodate visual acuity (Campbell & Gregory, 1960). Pupils constrict when the amount of light reaching the eyes increase, while decreasing light causes pupils to dilate. This phenomenon was named the *pupillary light reflex*: A change in pupil dilation in response to a change in luminance on the fovea.

More recent research on the pupillary modulation gives reason to think the pupillary light reflex might be more than a reflex (Binda, Pereverzeva, & Murray, 2013; Mathôt, Dalmaijer, Grainger, & Van der Stigchel, 2014; Mathôt, Van der Linden, Grainger, & Vitu, 2013). Mathôt and colleagues have shown this by conducting an experiment in which participants had to look at a central fixation dot on a screen with a bright and dark side (2013). The eyes of the participants had to stay focussed on the fixation dot to control for equal luminance in the fovea. Attention of the participant was then *covertly* drawn (without changing gaze) towards either the dark or the bright side of the screen. Despite the maintained equal luminance there were significant differences in pupil size between attending towards the dark and the bright side of the screen. When attending the bright side of the screen a relative constriction of the pupil was found while attending the dark side of the screen resulted in pupillary dilation. The detected modulation of the pupil could only have arisen from the manipulated covert attention and was thus contributed to an attentional component. This implies the pupillary response to light can be modulated by attention and thus cannot be purely a reflex. Consequently, this paper defines the *pupillary light response* (PLR) as a change in pupillary dilation resulting from a covert shift in spatial attention (without changing gaze, thereby not necessarily foveated).

To evoke a covert shift in spatial attention, *attentional cueing* can be applied as described by Posner in his cueing task paradigm (1980). The cueing of attention in the direction of a target enhances the response provoked by the target. If the cued location is in accordance with the target location (valid), the cue and target are *congruent*. When the cued location does not match the target location (invalid), then cue and target are *incongruent*.

The *behavioural effects* of attentional cueing can be measured by means of accuracy and response times (RTs). For valid cues this effect is *facilitating*, meaning accuracy is enhanced and RTs are decreased compared to invalid cues (Friesen & Kingstone, 1998). A stronger effect for a valid cue means stronger facilitation, while a stronger effect for an invalid cue implies stronger response enhancement at the cued location, where no response is required. Both of the effects result in behavioural modulation whereas only valid cues result in behavioural facilitation. Furthermore, facilitation is dependent on the time between the onsets of cue and target, known as the *stimulus onset asynchrony* (SOA). After the initial period of facilitation the effect can reverse at longer SOAs resulting in decreased accuracy and increased RTs, known as the *inhibition of return* (IOR).

The strength of the behavioural modulation has been found to correlate with the strength of the PLR modulation (Mathôt, Van der Linden, Grainger & Vitu, 2013). Specifically, the proportional change of the pupil size correlates with the change in behavioural measures. Accordingly, behavioural IOR is correlated with pupillary IOR as well. The strength of the PLR modulation in itself can be found by measuring pupil size over time and comparing this to the average pupil size during a baseline recording (prior to cue onset). The PLR modulation can then be expressed as a proportional change relative to the baseline. The change resulting from covertly cueing a dark surface is considered facilitating when positive (pupillary dilation). This congruence is independent of the validity of the cue. Subsequently, a negative change (constriction) when covertly attending a bright surface is also considered facilitating. When the pupillary modulation is incongruent with the brightness of the cued side, the pupillary response is considered *inhibitory*.

Notably, when the majority of trials are invalidly cued, the modulation of the PLR remains (Downing, Dodds, & Bray, 2004). Informing participants of cues being invalid does not alter the direction of enhanced attention. This indicates the modulation effects are resistant to relearning and cannot be consciously suppressed. Approximately 200 ms passes before the PLR modulation has its onset (Ellis, 1981). Depending on the participant and the task at hand, this latency can vary up to 500 ms.

Different methods of attentional cueing exist to bias attention in a direction. A common method is to shift the phase of a high-low contrast frequency, known as a Gabor pattern. This *exogenous* (externally caused) cue creates the illusion of a sudden movement which reflexively enhances attention at the cued location. Another type of cue is the *endogenous* (internally caused) cue, a symbolic directional representation intended to shift attention. This cue type is considered voluntary because the symbolic relation has to be learned before the cue can bias attention, as is the case with language (“look left”).

Utilizing these methods of cueing has shown PLR modulations can vary between cue types (Binda et al., 2013; Mathôt et al., 2014). Binda and colleagues utilized endogenous shifts of attention to show the resulting PLR has a late onset, long duration and no IOR (2013). Attending to dark stimuli induced a relative dilation compared to lighter stimuli, reflecting pupillary facilitation. The experiment done by Mathôt and colleagues made use of exogenous cueing (2014). The same initial facilitation was found with an earlier PLR onset and a shorter duration. Modulation lasted for approximately half a second followed by a reversal, reflecting pupillary IOR.

A third type of cue that has been shown to bias attention is the *gaze cue* (Driver et al., 1999; Friesen & Kingstone, 1998; Frischen et al., 2007; Hermens, 2015; Hietanen, 1999; Kemner, Schuller, & Van Engeland, 2006). The phenomenon found with gaze cueing is that a perceived directional gaze enhances attention in the direction of the gaze, resulting in behavioural facilitation. The responsible mechanisms are still a matter of debate in literature, with arguments being made for early learned behaviour (Hommel, Pratt, Colzato, & Godijn, 2001; Tipples, 2002) as well as evolutionary hardwired (Moore & Corkum, 1998; Bugnyar, Stowe, & Heinrich, 2004). Although it is unknown whether gaze cueing is reflexive (hardwired) or voluntary (learned), the resulting behavioural facilitation has been demonstrated in many studies.

We now ask whether gaze cues can result in attentional modulation of the PLR as well, in line with the findings for exogenous and endogenous cueing. Because of the known correlations between pupillary and behavioural modulations for exogenous and endogenous cueing, it is expected attentional modulation can be found for gaze cueing as well. Accordingly, the strength of PLR modulations is expected to correlate with the strength behavioural modulation.

The resulting pupil traces for proportional change are averaged per point in time for the attend-bright and attend-dark condition. The averaged trace per condition can then be compared across different types of cueing to explore any similarities or differences. If gaze cueing shows similarities with exogenous cueing an early onset of PLR modulation is expected, followed by IOR. Similarities with endogenous cueing should result in a late onset, long duration and no visible IOR. The absence of any modulation indicates gaze cueing is not affected by an attentional component. The final results could aid the ongoing research in the field of experimental psychology by broadening the available data on PLR modulations.

Experiment 1

Methods

Participants

All 11 participants (3 female, 8 male) in this experiment had normal or corrected to normal vision. All participants were healthy individuals recruited from the area surrounding Utrecht. One of the participants was diagnosed with autism spectrum disorder. All participants signed a consent form according to the Helsinki declaration and received a twelve euro reward for participating.

Apparatus

The experiment was conducted on two identical setups. A darkened room was used where the only light came from the ROG Swift PG278q, 27” LCD monitor (Luminance: 140 cd/m^2, Contrast: 500:1, Refresh Rate: 120 Hz, Resolution: 2560x1440). Participants let their heads rest on a chinrest to assure a stable image for the eye-tracker. Distance between the eyes and the monitor was 70cm, so one degree in visual angle corresponded to 122 mm of screen size (S = tan(V/2)*2D; where S=Size, V=visual angle, D=distance to screen). Surface of the screen was 60.7x35cm. The eye-tracker used was the EyeLink1000 (SR Research Ltd. Ottawa ON; Sample rate: 1000 Hz).

The experiment was written in Python, making use of the PyGaze Toolbox (Dalmaijer, Mathôt & Van der Stigchel, 2013). The face stimuli used were gathered from the MacBrain Face Stimulus Set (Tottenham et al., 2009). Five different faces (one female, four male) were used, with three gaze directions (left, right and neutral).

Measurements

Calibration of the eye-tracker used either the native 9-point or 5-point routine. Participants had to recalibrate if an in-between drift check failed or if the experimenter felt it was necessary. No active prevention of gaze deviation was applied. If participants’ gaze deviated more than two degrees from the fixation point during a trial, that trial was removed during analysis. A baseline recording for pupil size started 200 ms prior to cue onset.

Procedure

The used experimental paradigm was derived from similar experiments done by Mathôt et al. (2013, 2014). The experiment contained 32 blocks with 20 trials. Every four blocks the pause screen was presented with the current progress as a percentage of completion. During this break the light was turned on. Halfway through the experiment participants were advised to leave the dimly lit room and walk around in daylight for a moment. Each block was preceded by a drift-check procedure. During the drift check the participant had to fixate on a central dot and press the spacebar. If gaze deviation exceeded two degrees the drift-check failed and the eye-tracker had to be recalibrated, otherwise the experiment continued. Per block twenty trials were presented.

Every trial contained four phases: the adaptation, cue, target and response phase. The adaptation phase lasted 3000 ms and showed the grey background, a light (140 cd/m^2) and dark (0.28 cd/m^2) disk on top of a Gabor patch on either side and a central neutral gaze face with a white fixation dot at its centre (figure 1: adaptation). The two disks were 7 ° in diameter and were positioned 9 ° from the central fixation dot.

In the cue phase, one of two possible cue types was presented, either the gaze cue or the exogenous cue. In case of the gaze cue the eyes of the neutral faces looked either to the left or to the right and stayed in this position (figure 1: cue). With the exogenous cue type the Gabor patch shifted phase for 100 ms and then stopped, creating the illusion of a sudden movement. After a SOA of either 100, 1000 or 2000 ms the target phase started. In the target phase, a target and a distractor appeared at the centre of the two disks. Prior cues did not predict the target location. The target could be one of two orientations: normal (‘T’) or upside-down (‘⊥’). The distractor appeared at the same moment and contained both orientations, resembling a capital ‘I’ (figure 1: target). The target was visible for 250ms after which the response phase started. At the onset of the response phase, the target was covered with its counter-part, making the target and distractor of equal appearance (figure 1: mask). The response phase lasted for three seconds or until a response was recorded. To respond correctly, the participant had to press the up arrow if the target was in normal orientation and the down arrow if the target was inverted. If no response was recorded within three seconds, a time-out was registered and the experiment continued to the next trial. Participants received no feedback about correct responses during the experiment. During the experiment, participants had to maintain a central gaze. The duration of the experiment was dependent on the speed of the participant and the desire to utilize break time. In total, the experiment lasted approximately two hours.

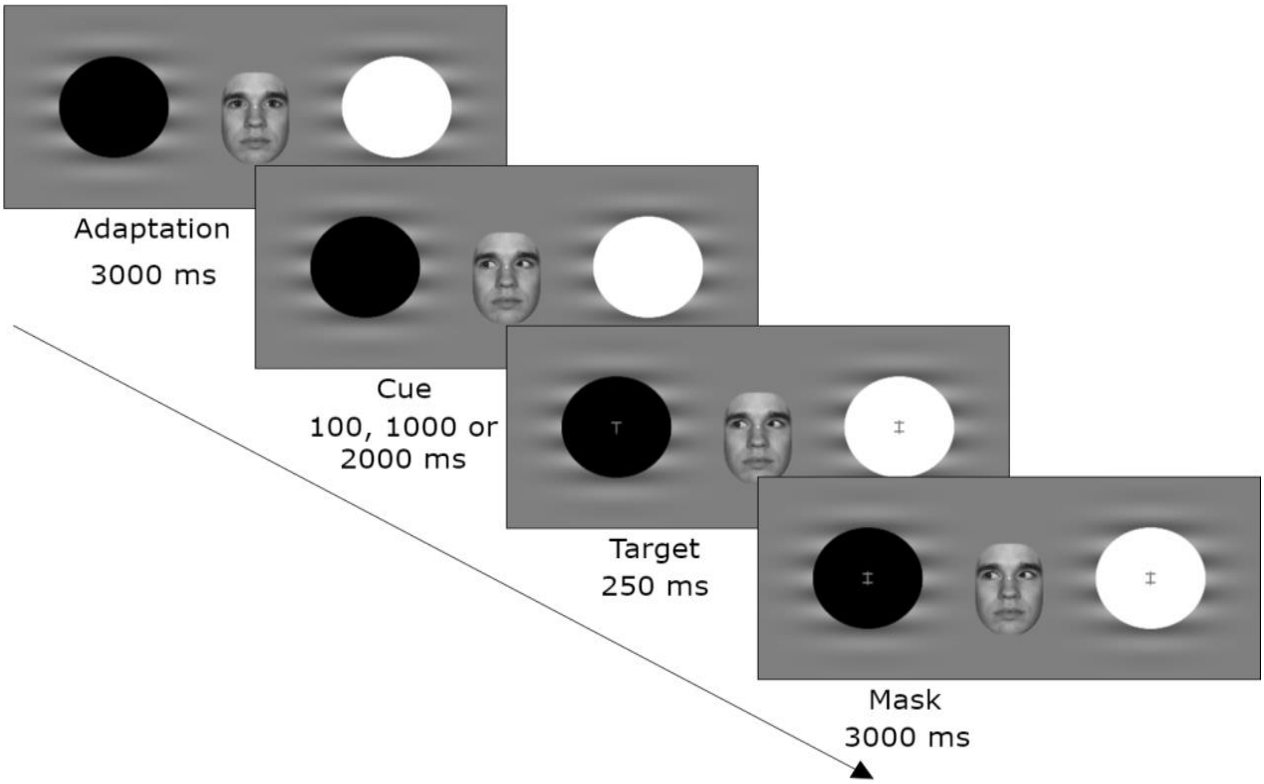

Figure 1. Detailed view of the four phases in a single trial.

Conditions

The trials per cue type were evenly divided: 50 percent of the 640 trials were exogenous while the other half used the gaze cue. The same principle was used for disk luminance (dark/bright), cue direction (left/right), target location (valid/invalid) and target orientation (up/down); resulting in 20 trials in each of these conditions (640/(2^5)). These twenty trials were divided over the three different SOAs: one quarter with 100 ms, another quarter with 1000 ms and half with 2000 ms. The 2000 ms SOA outweighs the other SOAs because the lengthened asynchrony yields longer pupil traces for analysis (cf. Mathôt et al., 2014; Mathôt et al., 2013). Each of the quarters contained five trials for which the different face stimuli were evenly used. This setup resulted in 48 unique trials in the exogenous condition and 240 unique trials in the gaze condition. The complete list of trials was presented in a randomized order.

Analysis

To analyse results the Python script PyGazeAnalyzer provided by Dalmaijer and colleagues was used (Dalmaijer, Mathôt & Van der Stigchel, 2013). This analyser orders raw gaze data and behavioural data to draw individual and averaged plots of the pupil traces. When a time window holds a significant difference in pupil traces, coloured shading was applied.

A total of 640 trials per participant amounted to 7040 recorded trials. If participants scored close to or lower than 50 percent correct, the results were not evaluated. Because the task used a dichotomous response (either up or down), 50 percent correct is expected by chance alone and is thus considered the *guessing threshold*. Two of the eleven participants were excluded because of this this criterion. The behavioural analysis had no other exclusion criteria so accuracy and mean RTs were calculated on this pool ($N = 5760$).

To evaluate the behavioural aspects of accuracy and RTs two repeated measures ANOVA’s were used with three factors. The factor Cue had two levels: exogenous and gaze, the factor Validity had the valid and invalid level and the factor SOA had the 100, 1000 and 2000 ms level. Related samples t-tests were performed to compare valid and invalid trials per Cue and SOA.

For the pupillary analysis only the 2000 ms SOA condition was evaluated because this yields the longest pupil trace without the interference of a manual response ($N = 2880$). Only trials where the gaze deviated no more than two degrees from the fixation dot were entered into the analysis. If an incorrect response or a time-out was recorded on any trial, that trial was excluded as well.

Blink interpolation was used when possible to correct for missing data during blinks. If enough data was available a cubic spline interpolation was used, otherwise a linear interpolation was applied (see for description: Mathôt, 2013). Hampel filtering was used to find outliers; data which deviated more than two standard deviations from the running median were replaced by this median. The within subject error of the mean was calculated according to Cousineau (2005).

Significant differences for every millisecond in the time window were determined with t-testing. It is important to note that t-testing is expected to result in an approximate 100 significant results by sheer chance (five percent of data). A correctional measure like Bonferroni where the alpha is divided by the number of t-tests would results in such a small alpha that significance would become very improbable ($\alpha / 2000 = 2.5\times10^{-5}$). Furthermore, the independence assumption for multiple comparison corrections does not apply because pupil data tends to be very highly correlated. For this reason, no stringent corrections were applied.

Two conditions of interest per cue type were evaluated in the pupillary analysis: attend-bright and attend-dark, determined by the brightness of the cued disk during the trial.

The baseline per trial was calculated by taking the median pupil size from 200 ms prior to cue onset up until the cue onset. The remaining trace for the trial was then divided by the baseline to reflect a relative increase in pupil size. For each participant the relative pupil sizes were averaged over the different conditions. This resulted in individual datasets per cue type for attend-bright and attend-dark. The individual results were then averaged over all participants to yield four averaged datasets. These datasets could then be plotted in one graph per cue type.

Results

Behavioural

A repeated measures ANOVA was performed on the behavioural data. No main effects for either the accuracy data or the RT data were found. No significant interactions between Cue, Validity or SOA were demonstrated. This means the current data are inadequate for describing the behavioural cueing effects hypothesized. It is possible this is the result of a ceiling effect for accuracy (figure 2, top row; $M = .942$, $SE = .014$). Furthermore two of the eleven participants were excluded due to not reaching the 50 percent correct guessing threshold. Besides decreasing the usable data by eighteen percent, this also indicates the experiment needs methods of preventing unusable data due to either too high or too low accuracy. Expanding the number of participants should increase the likelihood for significance as well.

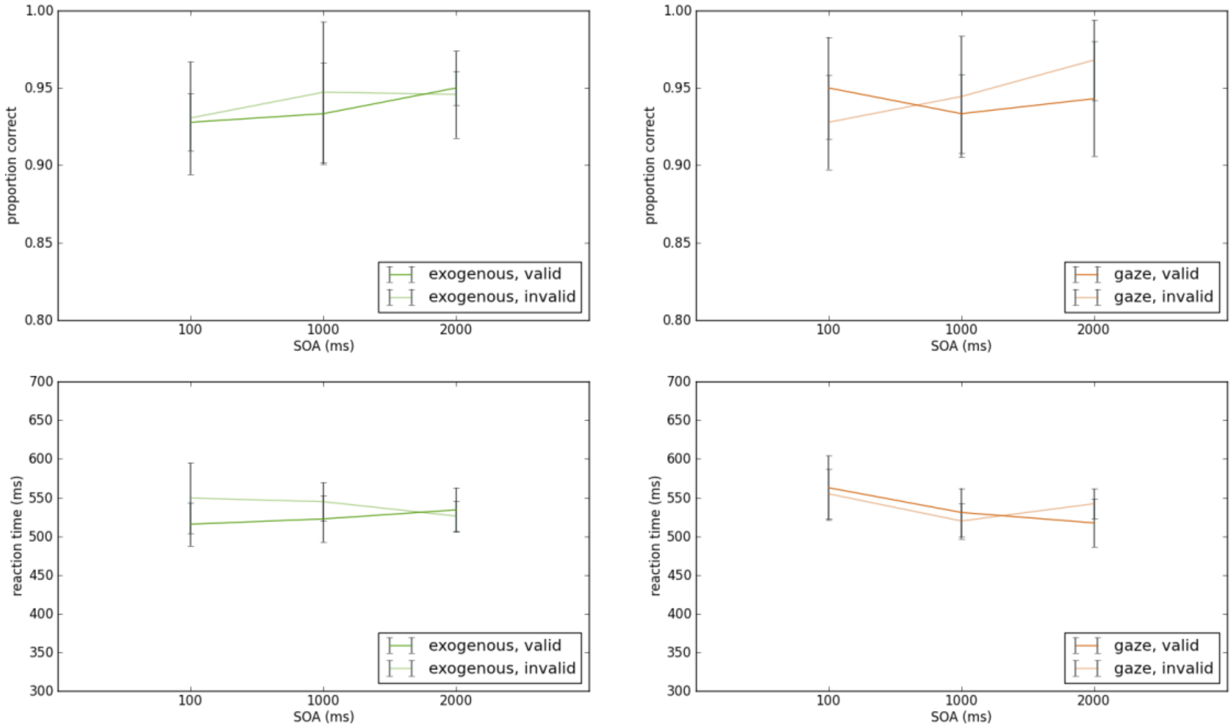

Figure 2. The behavioural effects of exogenous (green) and gaze (orange) cueing of attention. Top row displays accuracy data in proportion correct, bottom row show RTs in ms. Error bars are the within-subjects standard error of the mean.

Pupillary

Significant differences in pupil size were found between the attend-bright and attend-dark conditions for both cue types (figure 3). In the exogenous cueing condition the difference in pupil size was significant between 88 and 169 ms as well as between 568 and 1167 ms. This result was unexpected because the difference in the early time window seems too soon to be explained by a pupillary facilitation effect. Secondly, the onset of the second time window (568 ms) does match while the offset (1167 ms) is much later than reported by Mathôt et al. (2014). This suggests longer pupillary facilitation than reported earlier. Furthermore, no inhibition of return was found following the facilitation.

In the gaze cueing condition the difference in pupil size was significant between 32 and 81 ms after cue onset as well as between 874 and 920 and lastly between 944 and 1195 ms. In the earliest time window (32 to 81 ms) the pupil was less dilated in the attend-dark condition, while in the other two time windows the pupil was less dilated in the attend-bright condition. The difference in the earliest window was unexpected because pupillary facilitation usually takes up to 400 ms (Mathôt, 2013). The latter differences were slightly later than expected but still suggest pupillary facilitation following the gaze cue. No IOR was found in this condition either, which is in line with the absence of effects for the behavioural data, since pupillary and behavioural IOR are thought to be correlated. However, no correlation between behaviour and pupil was found in our data.

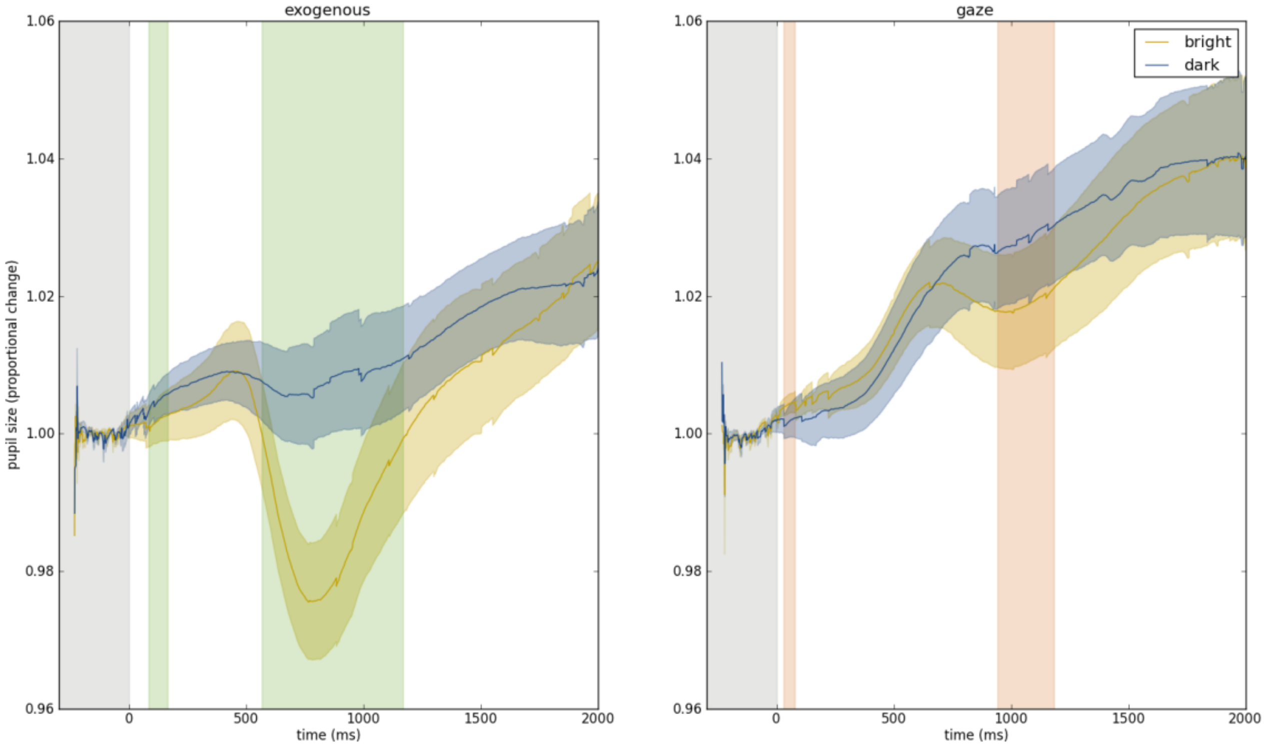

Figure 3. Proportional pupil size in the exogenous condition (left) and gaze condition (right). The shadings indicate significant differences between attend-bright (yellow line) and attend-dark (blue line).

The results from this experiment did not show the effects that were expected. To minimize unusable data a second experiment was conducted with a few differences implemented. Most importantly: the distractor was removed, the mask was randomized and target duration was made adaptive.

Experiment 2

Methods

Participants

Twenty participants took part in this experiment (12 female, 8 male).

Design

The second experiment was mostly identical to the first experiment with a few minor differences. Instead of a fixed target duration of 250 ms, a stepwise 3-up-1-down staircase was implemented to vary the target duration (Cornsweet, 1962). This assured an approximate 80 percent correct so participants would not need to be excluded for not reaching the guessing threshold.

Prior to starting the experiment a practice block of ten trials was added. This allowed participants to get used to the speed of the task and ask questions if anything remained unclear. Implementing the practice rounds improved the amount of valid results from the start of the experiment.

Furthermore, some of the prior participants mentioned they made use of the mask onset as an indicator for which target was shown. To prevent this from happening, a set of random lines was implemented as masking (see figure 4: mask). The distractor was removed to lower competition and no masking was shown on the untargeted side of the screen (see figure 4: target).

The last change that was implemented concerned feedback on the pause screen. A percentage correct was added to let participants know how well they were doing. Because of the staircase this percentage was always at or around 80 percent. At the end of the experiment the final target duration was displayed as well.

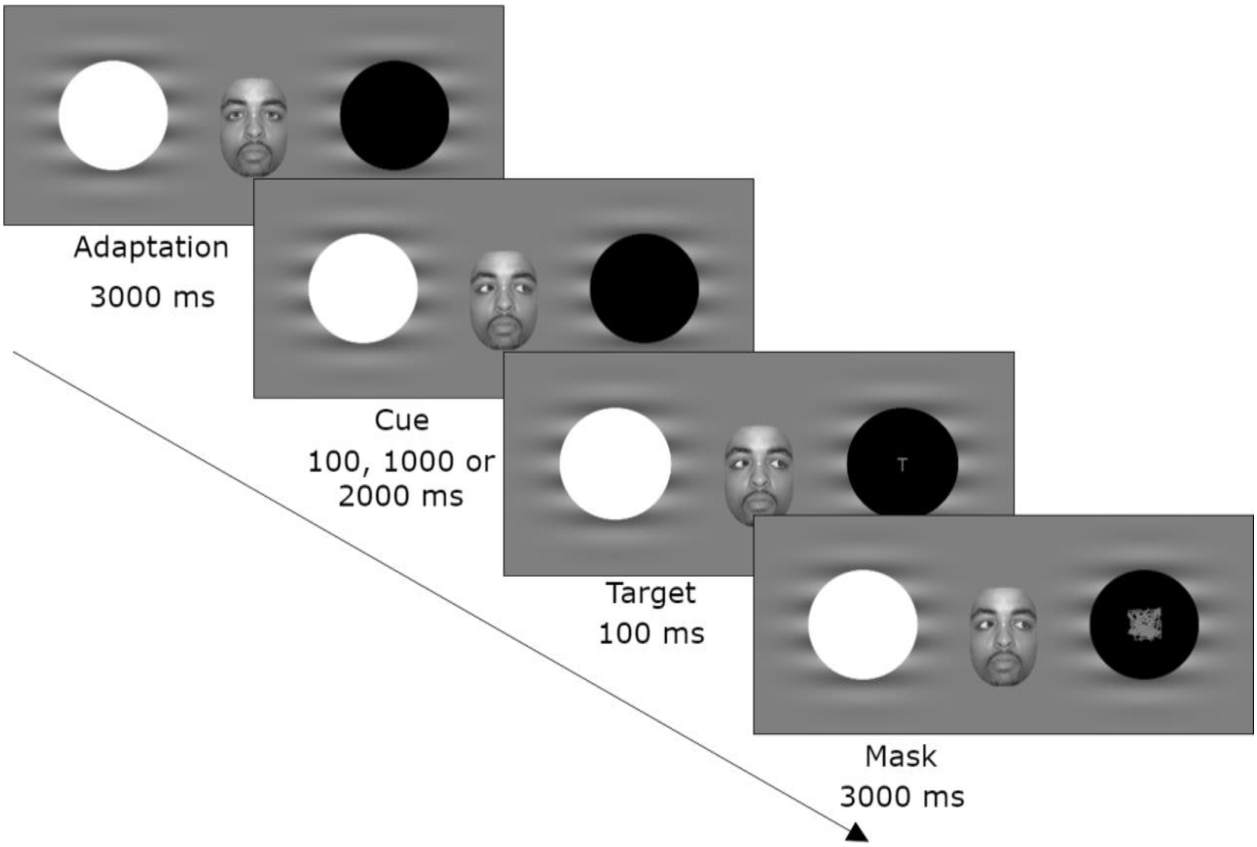

Figure 4. Detailed view of a single trial.

Analysis

One participant was excluded because the pupil trace data got corrupted. The remaining nineteen traces were all entered into the analysis.

Results

Behavioural

A main effect for accuracy was found for SOA ($F(1,1.93) = 12.53$, $p < .001$, Greenhouse-Geisser corrected). This implies the observed accuracy for a participant is influenced by the length of the SOA, with longer SOAs resulting in increased accuracy. An interaction effect between Cue and SOA was found as well ($F(1,1.80) = 8.26$, $p = .002$, Greenhouse-Geisser corrected). This means the combination of Cue and SOA together have an effect on the resulting accuracy. The 100, 1000 and 2000 ms SOA each showed an increase in accuracy for the gaze cue, whereas the exogenous cue only showed this increase at the 2000 ms SOA. This is an indication for the absence of IOR, which is unexpected. No Validity effect was found for accuracy.

Tests of Within-Subjects Effects

Measure: Accuracy

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
SOA	.061	1.927	.032	12.532	.000
Cuetype * SOA	.029	1.798	.016	8.262	.002

Table 1. Significant effects for accuracy.

For the RTs a main effect was found for SOA(F(1,1.79) = 8.64, p = .001, Greenhouse-Geisser corrected) and Validity (F(1,1) = 4.40, p = .05, Greenhouse-Geisser corrected), implying RTs are affected by Validity as well as the length of the SOA. Longer SOAs and valid cues both resulted in a slightly decreased RT, showing behavioural facilitation. This is in line with the expected difference of valid RT < invalid RT. However, this effect did not reach significance when separately comparing Validity per Cue and SOA condition.

An interaction effect between Cue and SOA was found for RT (F(1,2) = 11.15, p < .001, Greenhouse-Geisser corrected). So the combination of these two affects RTs as well as accuracy. For the gaze cue the RT was shortest in the 1000 ms SOA and longest in the 100 ms SOA. The exogenous cue showed a decrease in RT for each increased SOA. The decreased RT for the 2000 ms SOA in the gaze cue condition might be due to IOR, although the expected IOR in the exogenous condition was not found.

Tests of Within-Subjects Effects

Measure: ResponseTime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
SOA	39607.457	1.792	22107.444	8.644	.001
Validity	11960.667	1.000	11960.667	4.394	.050
Cuetype * SOA	24827.874	1.684	14747.630	11.150	.000

Table 2. Significant effects for behavioural RTs.

Pupillary

Multiple time windows where pupil traces differed significantly were found in the exogenous condition (figure 5, green shading). The difference between attend-bright and attend-dark was significant between 203 and 382 ms, 405 and 479 ms, 485 and 560 ms and lastly between 691 and 1744 ms. In each of these significant windows the pupil was more dilated in the attend-dark condition, reflecting pupillary facilitation.

In the gaze condition two time frames were found to hold significantly different traces (figure 5, red shading). The first window was between 390 and 459 ms, and the second between 1167 and 1948 ms. In both these windows the pupil was significantly more dilated in the attend-bright condition than in the attend-dark condition. This suggests pupillary inhibition for the attend-bright condition compared to attend-dark.

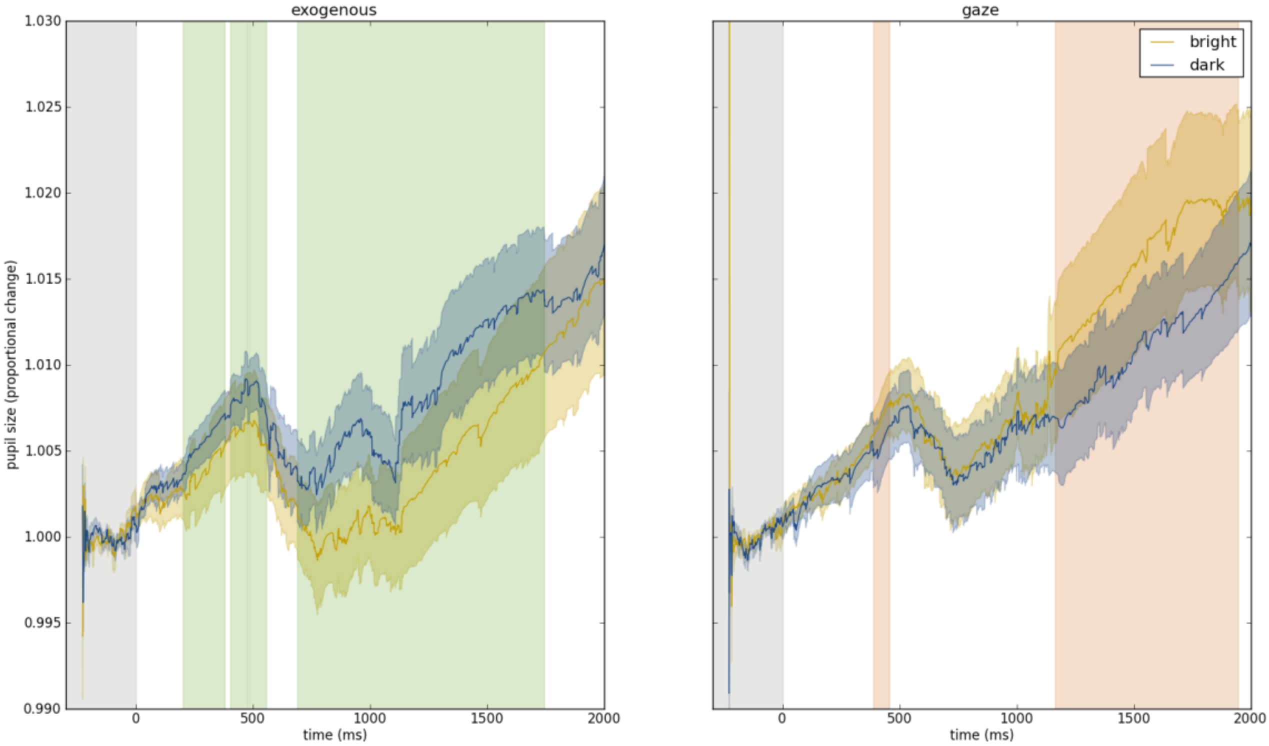

Figure 5. Proportional pupil size in the exogenous condition (left) and gaze condition (right). The shadings indicate significant differences between attend-bright (yellow line) and attend-dark (blue line).

Cumulative results

As a means of exploration, the data from both experiments were taken together and analysed in the same way as described earlier (*N*=28). This can rule out issues with insufficient statistical power.

Behavioural

The same main effect for accuracy was found for SOA ($F(1,1.92) = 14.33$, $p < .001$, Greenhouse-Geisser corrected). The interaction effect between Cue and SOA remained significant as well ($F(1,1.90) = 5.62$, $p = .007$, Greenhouse-Geisser corrected). The expected Validity effect did not reach a level of significance.

Tests of Within-Subjects Effects

Measure: Accuracy

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
SOA	.060	1.918	.031	14.326	.000
Cuetype * SOA	.018	1.896	.009	5.616	.007

Table 3. Significant effects for accuracy.

For the RTs a main effect for SOA was found (*F*(1,1.75) = 11.06, *p* < .001, Greenhouse-Geisser corrected). Validity as a main effect reached significance as well (*F*(1,1) = 6.68, *p* = .015, Greenhouse-Geisser corrected), in line with the expected difference of valid RT < invalid RT. The interaction effect between Cue and SOA remained significant (*F*(1,1.65) = 13.24, *p* < .001, Greenhouse-Geisser corrected).

Tests of Within-Subjects Effects

Measure: ResponseTime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
SOA	43417.287	1.750	24808.300	11.056	.000
Validity	13603.940	1.000	13603.940	6.684	.015
Cuetype * SOA	29010.303	1.645	17634.841	13.241	.000

Table 4. Significant effects for RTs.

A paired samples t-test was conducted to compare Validity in Cue and SOA. The results showed only the 100 ms SOA in the exogenous cue condition remained significant (*t*(27) = -2.34, *p* = .027), meaning participants where faster to respond to valid exogenous cues at the 100 ms SOA.

Paired Samples Test

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference: Lower	Upper			
(Exogenous, 100ms, Valid) - (Exogenous, 100ms, Invalid)	-28.1273	63.5177	12.0037	-52.7569	-3.49772	-2.343	27	.027

Table 5. Significant results for the paired samples test.

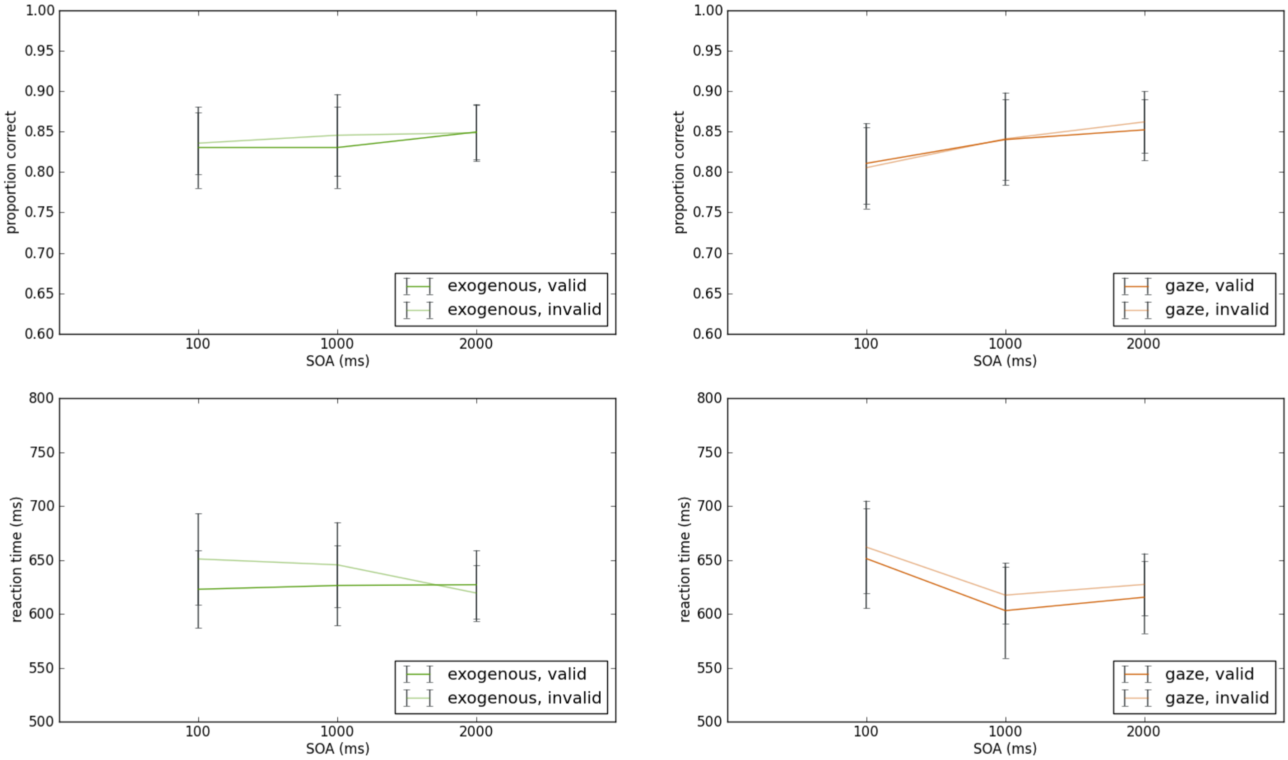

Figure 6. The behavioural effects of exogenous (green) and gaze (orange) cueing of attention. Top row displays accuracy data in proportion correct, bottom row show RTs in ms. Error bars are the within-subjects standard error of the mean.

Pupillary

The significant differences in pupil size for the exogenous condition differed slightly from the earlier analyses. The difference was significant between 72 ms and 399 ms as well as between 486 ms and 1784 ms (figure 7, green shading). For both these time windows the pupil was constricted in the attend-bright compared to the attend-dark condition, reflecting facilitation.

The gaze condition yielded multiple significant differences in relatively small time windows. Up until 582 ms the differences reflected inhibition, from 865 ms until 1135 ms facilitation was seen and from 1556 ms to 1872 ms this reverted back to inhibition (figure 7, red shading).

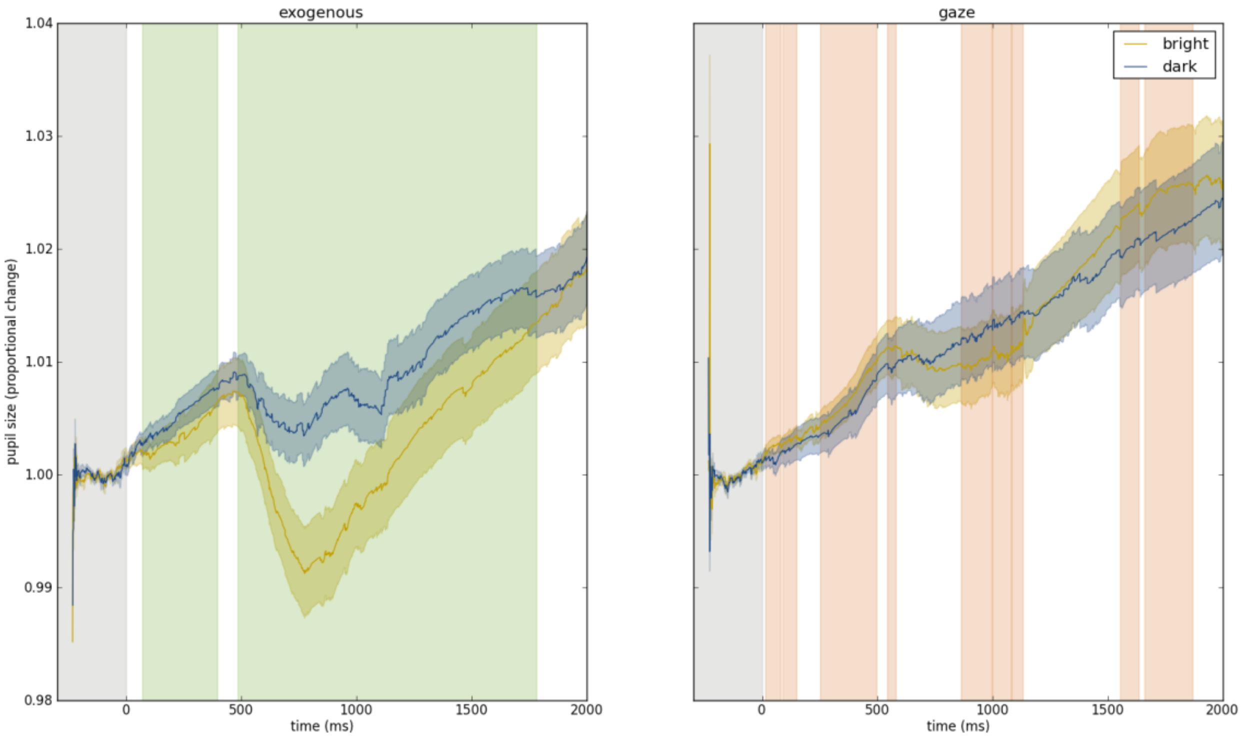

Figure 7. Proportional pupil size in the exogenous condition (left) and gaze condition (right). The shadings indicate significant differences between attend-bright (yellow line) and attend-dark (blue line).

General Discussion

The purpose of the experiment was to find attentional modulation of the PLR in response to gaze cueing. In the gaze condition we expected to see early behavioural facilitation and a late offset with no IOR (Binda et al., 2013; Friesen et al., 1998). For the pupillary facilitation we expected a later onset between 200 and 500 ms and a long duration (Binda et al., 2013; Mathôt et al., 2013; Ellis 1981). In the exogenous condition we expected the behavioural and pupillary facilitation to be comparable with an early onset and IOR, since both facilitations are found to be correlated (Mathôt et al. 2014).

Our current data could not confirm these expectations. We found no behavioural facilitation in the gaze cueing condition for any of the three analysed datasets. For the exogenous condition behavioural facilitation was visible for the 100 ms SOA in the RT data. No IOR was found in any of the behavioural data.

Pupillary facilitation in the gaze condition did reach significance for certain time windows. The facilitation onset was later than expected (as late as 865 ms in the combined dataset) and lasted up to 1135 ms after cue, which does not reflect the expected long duration. The facilitation converted to inhibition from 1556 ms to 1872 ms. This is not a strong indication for IOR, since inhibition is expected to last longer.

The onset for pupillary facilitation in the exogenous condition was at 72 ms for the combined dataset. This is earlier than expected from the PLR latency of 200 to 500 ms. Facilitation peaked around 750 ms and lasted up to the 1784 ms mark. No significant IOR was found after the peak in facilitation. The lack of visible IOR in the exogenous pupillary data is congruent with the absence of an IOR response in the behavioural data, even though no correlation was found between the behavioural and pupillary data.

The results did not confirm our expectations. The possible causes for this remain a matter of critical retrospection. The addition of the combined dataset analysis showed that statistical power is not the issue, adding the datasets together only added significance for the effect of Validity on RTs at the 100 ms SOA. Strikingly, the plotted pupil data show strong variance in the baseline. Since the first 200 ms of pupil sizes are averaged and used as reference for the proportional change, this is highly unexpected. This could indicate artefacts in the data that have not been recognized by the Hampel filtering method. If this is the case, the reliability for the rest of the data is diminished as well, most likely resulting in decreased significance. The fact that most of the pupil plots show irregularities such as spikes and dents, gives reason to doubt the exactness of the data as well. Adding an exclusion criterion to control for the maximum speed at which pupils can increase and decrease in size could help filtering out faulty data.

At times during the experiment the eye-tracker equipment could lose track of the pupil, not registering any data in this timeframe. The experiment did not utilize any real-time controls for exceeding maximum deviation or loss of signal, meaning faulty data could not be actively prevented. In this case we rely on the filtering methods to exclude these trials, even though ideally no faulty trials would end up in the analysis dataset. Utilizing a setup where the screen actively adapts its image to the actual gaze direction should strongly minimize trials excluded due to exceeded deviation. This would also ensure a continuous equal luminance on the fovea during a trial.

Some of the participants mentioned to have trouble with the length of the experiment. After a while complaints about dryness of the eyes were common, resulting in an increase in blink amount as well as duration. As a result, less clean traces could be recorded for these participants. The eight implemented breaks might not have been enough for some participants. Furthermore, when participants' eyes get tired the eyelids tend to lower, which can affect the data recorded by the eye-tracker because of a partially concealed pupil.

In the second experiment task engagement was assured by adapting the difficulty of the task to the participant's capability. However, feedback was minimal so there was no real incentive to perform better. Besides adding accuracy feedback about performance up until the current trial, feedback for RT and accuracy per block could increase task engagement.

The adaptive staircase used was capped at a minimum of 0ms to assure target duration could not go in the negative numbers. However, some of the participants managed to reach the 0 ms limit, effectively removing the target from these trials. This also caused an offset of the target duration by 6 ms for the rest of the experiment, indicating these data are not as clean as we aimed for. This has been an error in the program which was discovered after most of the experiments were completed.

There are other known nonvisual means that influence pupil size. Examples include cognitive effort, task engagement, memory load or startling effects (Binda et al., 2013). Even though these effects cannot be ruled out, it is assumed these effects will even out over the different conditions due to the proportional comparison. The progressive dilation that can be seen in the plots for pupil size can in this sense be explained by the cognitive effort required for the task.

Conclusion

No attentional modulation of the PLR was found for the gaze cueing condition. As mentioned earlier, the absence of modulation could indicate gaze cueing is not affected by an attentional component. However, the known effects like IOR and cueing strength correlation could not be replicated either. This leads to the conclusion that the current experimental design can neither confirm nor reject the hypothesis.

Suggestions

In an effort to increase the potential of the experimental design, suggestions for future modifications are discussed here.

First and foremost, active prevention of unusable data due to gaze deviation should improve results. The implementation can be realised in a variety of ways, where automatically shifting the displayed image according to current gaze position (retinal stabilization) is preferred due to continuation. Adding the option for the experimenter to pause the experiment at any given time could decrease the unusable trials due to signal loss and also allow participants to request a break when needed.

Increasing the size of the bright and dark disks should enhance the resulting PLR due to the increased difference in local luminance. An increased PLR should in turn cause a more apparent modulation effect to be visible in the data. Task engagement could be increased to ascertain stronger cueing effects, which should also increase the PLR modulation. One of the aforementioned methods to realize this is to add comparable statistical feedback to the break screens, which could give participants an incentive to better themselves and thus result in less attentional digression.

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Literature

Binda, P., Pereverzeva, M., & Murray, S. O. (2013). Attention to bright surfaces enhances the pupillary light reflex. *The Journal of Neuroscience,33*(5), 2199-2204. http://doi.org/10.1523/JNEUROSCI.3440-12.2013

Bugnyar, T., Stöwe, M., & Heinrich, B. (2004). Ravens, Corvus corax, follow gaze direction of humans around obstacles. *Proceedings of the Royal Society of London B: Biological Sciences*, *271*(1546), 1331-1336. http://doi.org/10.1098/rspb.2004.2738

Campbell, F. W., & Gregory, A. H. (1960). Effect of size of pupil on visual acuity. *Nature*, *187*(4743), 1121-1123. http://dx.doi.org/10.1038/1871121c0

Cornsweet, T. N. (1962). The staircase-method in psychophysics. *The American journal of psychology*, *75*(3), 485-491. doi:1. http://www.jstor.org/stable/1419876 doi:1

Cousineau, D. (2005). Confidence intervals in within-subject designs: A simpler solution to Loftus and Masson's method. *Tutorials in quantitative methods for psychology*, *1*(1), 42-45.

Dalmaijer, E.S., Mathôt, S., & Van der Stigchel, S. (2013). PyGaze: an open-source, cross-platform toolbox for minimal-effort programming of eye tracking experiments. *Behaviour Research Methods*. doi:10.3758/s13428-013-0422-2

Downing, P., Dodds, C., & Bray, D. (2004). Why does the gaze of others direct visual attention? *Visual Cognition, 11*(1), 71–79. http://doi.org/10.1080/13506280344000220

Driver, J., Davis, G., Ricciardelli, P., Kidd, P., Maxwell, E., & Baron-Cohen, S. (1999). Gaze Perception Triggers Reflexive Visuospatial Orienting. *Visual Cognition, 6*(5), 509–540. http://doi.org/10.1080/135062899394920

Ellis, C. J. (1981). The pupillary light reflex in normal subjects. *British Journal of Ophthalmology*, *65*(11), 754-759.

Friesen, C. K., & Kingstone, A. (1998). The eyes have it! Reflexive orienting is triggered by nonpredictive gaze. *Psychonomic Bulletin & Review, 5*(3), 490–495. http://doi.org/10.3758/BF03208827

Frischen, A., Bayliss, A. P., & Tipper, S. P. (2007). Gaze cueing of attention: Visual attention, social cognition, and individual differences. *Psychological Bulletin, 133*(4), 694–724. http://doi.org/10.1037/0033-2909.133.4.694

Hermens, F. (2015). Fixation instruction influences gaze cueing. *Visual Cognition, 23*(4), 432–449. http://doi.org/10.1080/13506285.2015.1042539

Hietanen, J. K. (1999). Does your gaze direction and head orientation shift my visual attention? *NeuroReport, 10*(16), 3443–3447.

Hommel, B., Pratt, J., Colzato, L., & Godijn, R. (2001). Symbolic Control of Visual Attention. *Psychological Science, 12*(5), 360–365. http://doi.org/10.1111/1467-9280.00367

Kemner, C., Schuller, A.-M., & Van Engeland, H. (2006). Electrocortical reflections of face and gaze processing in children with pervasive developmental disorder. *Journal of Child Psychology and Psychiatry, 47*(10), 1063–1072. http://doi.org/10.1111/j.1469-7610.2006.01678.x

Mathôt, S., Dalmaijer, E., Grainger, J., & Van der Stigchel, S. (2014). The pupillary light response reflects exogenous attention and inhibition of return. *Journal of Vision, 14*(14), 1–9. http://doi.org/10.1167/14.14.7

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

Mathôt, S. (2013). A simple way to reconstruct pupil size during eye blinks. *Figshare, 688001*. http://dx.doi.org/10.6084/m9

Moore, C., & Corkum, V. (1998). Infant gaze following based on eye direction. *British Journal of Developmental Psychology, 16*(4), 495–503. http://doi.org/10.1111/j.2044-835X.1998.tb00767.x

Posner, M. I. (1980). Orienting of attention. *Quarterly journal of experimental psychology*, *32*(1), 3-25.

Tipples, J. (2002). Eye gaze is not unique: Automatic orienting in response to uninformative arrows. *Psychonomic Bulletin & Review*, *9*(2), 314-318.

Tottenham, N., Tanaka, J. W., Leon, A. C., McCarry, T., Nurse, M., Hare, T. A., Nelson, C. (2009). The NimStim set of facial expressions: Judgments from untrained research participants. *Psychiatry Research, 168*(3), 242–249. http://doi.org/10.1016/j.psychres.2008.05.006

Appendix

The current experiment was purposefully designed to aid the research on attentional cueing. More research in this field could eventually allow reliable ways of cueing spatial attention. Concepts like these could then be deployed in any situation where human attention needs to be directed. An artificial intelligence that has learned about these relations could use this information to direct attention to a location of interest.

For example: In the world of gaming technology, artificial intelligence uses player data to predict patterns and try to actively hinder or counter the players as an opposing force. Making use of live pupillary data would provide insights in the players attended locations within the digital environment. This data can then be used to provide an attentional heat map of the playing environment. With this heat map the difficulty of the game can be altered, by allowing the opposing AI to avoid the most attended locations and only use the paths that are attended the least. On the other hand, the allied AI could use the known cueing mechanisms to direct players' attention towards locations of interest. The gaze cue in itself could prove to be a very efficient way of conveying directions to human players.