Figures’ note for FLI-Anistropy

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06 September, 2022

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# Article information

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# Methods

### Participants

Seventy-three volunteers (24 men; 49 women; mean age = 24.9, SD = 4.13) participated in the experiment. Eight were excluded from the analysis because they failed to fit with a psychometric curve (see Statistical Analysis section). The experiment lasted approximately 15 min, and all participants were compensated for their time (100 NOK). All experimental procedures were in accordance with the ethical principles outlined in the Declaration of Helsinki and approved by the Committee at the Oslo university. The experiment was performed in accordance with the approved guidelines of the committee and all participants provided written informed consent. Participant data and experimental scripts are available from <https://github.com/suzuki970/PupilFLE>.

### Stimulus and apparatus

The xy coordinates of the background and objects were 0.350 and 0.365 in the CIE1931 color space. The luminance of the stimuli was calibrated using a Spyder 4 Elite photometer (Datacolor Imaging Solutions, Lawrenceville, NJ), which indicated the background was 28.41 cd/m2. The luminance of the flashed and moving bars was 71.66 cd/m2. All stimuli were presented on 22 in. LCD monitor (P2210, Dell., Round Rock, US) with a resolution of 1680 x 1050 and a refresh rate of 60 Hz. The visual angle of the flashed and moving bars were 1.5° x 0.1° and 1.0° x 0.1° respectively. The trajectory of the moving bar was from 4.5° to 2.5° away from the center of the monitor. The bar moved horizontally toward within 500 ms so that the moving speed was 4°/s and. The flashed object was located at 2.5° x 2.75° from the center. The fixation point of 0.2° was located at the center. Each participant’s chin was fixed at a viewing distance of 600 mm. The task was conducted in a darkroom and executed by Experiment Center (SMI, Berlin, Germany).

### Procedure

The experiment was beginning with a five-point eye calibration. Figure 1 illustrates the experimental procedure. In each trial, a fixation point presented for 2,000 ms prior to the presentation of the stimulus. The moving bar appeared flash-lag stimulus at left/right for 50 ms and then started moving toward the center of the screen. During the presentation, the flashed bar appeared for 16 ms at each 8 SOA SOAs of -83.3, -66.7, -50.0, -33.3, -16.7, 0.0, 16.7 and 33.3 ms relative to the middle of presentation (i.e., 250 ms). Then, participants asked to answer whether they perceived the moving bar at the left or right of flashed bar using a keypad (Figure 1A). Each trial was separated by an inter-stimulus interval (ISI) of 2,000 ms. In the first block, the stimulus presented on LVF side of the screen for half of the participants and on RVF for another half. The second block was tested by the opposite visual field from the first block. Thus, total number of trials were 160 (2 visual fields(VFs) × 8 SOAs(or Lags?) × 10 repetitions).

### Recording and analysis of pupil size

Pupil size and gaze position were measured by a SensoMotoric Instruments RED500 (SMI, Berlin, Germany) eye-tracking system at a sampling rate of 60 Hz. An eye movement was measured at a resolution of about 0.01°. Pupil data during eye-blinks, obtained as the values of zero in the data and more than ±3 standard deviation of the first derivative of pupil data within each session and participant, were interpolated by piecewise cubic hermite interpolation. The trial including the pupil changes in more than 12 mm/s were excluded from the analysis (the mean rejected trials were 1.124 and SD = 1.282 out of 10 trials). The analyses in the present study were based on pupil diameters calculated in z-score (z) within the session for each participant. Baseline pupil size was computed as an average of data collected during the fixation period prior to stimulus onset from -500 ms to 0 ms (i.e., presentation onset). The pupillary data in each trial were baseline-corrected by subtracting the baseline pupil size, following which smoothing of each data point with ± 30 ms. Across SOAs, the pupillary response was averaged from the presentation period of stimulus onset to offset.

### Statistical analysis

The averaged probability of participants answering whether the moving bar was perceived ahead of flashed bars was fit with a psychometric curve using a maximum-likelihood logistic function. We estimated a Point of subjective equality (PSE) as the flash-lag effect at the probability of 0.5. After collecting PSE data at LVF and RVF for all observers, we performed pairwise t-test on a PSE between the visual fields. To statistically assess whether the FLE differed between VFs, PSE in each visual field were first bootstrapped 2000 times to estimate the mean and confidence interval. Mean pupillary changes are subjected to a two-way repeated-measures analysis of variance (ANOVA) with VFs and Lags as the within- subject factor. Pairwise comparisons of the main effects were corrected through multiple comparisons using the Bonferroni-Holm method. The level of statistical significance was set to p < 0.05 for all analyses. Effect sizes were given as partial ; for ANOVAs and as Cohen’s for -tests {Cohen.1989}. Greenhouse-Geisser corrections were performed when the results of Mauchly’s sphericity test were significant. To quantify the evidence in the data, we performed Bayesian paired t-tests and computed Bayes factors (BF) using a Cauchy prior width of r = 0.707 for effect size (v0.9.12-4.2) {Morey.2018kwf} for the R software (Version 3.6.3) {Team.2016}. We reported Bayes Factor (BF) estimating the relative weight of the evidence in favor of over as .

To compare the mean RT across SOA, we used a linear and nonlinear mixed-effects modeling with participant as a random effect to fit the data using the lme4 packages {Bates.2015}. In the analysis, we fitted the following two models to assess whether the pupil change variability () can be explained by the lag () using a second-order polynomials or monotonic fitting.

Model 1 :

Model 2 :

where as regression coefficients. The models were quantified using the Akaike information criterion (AIC), which specifies the evidence of goodness of fit for a model.

# Results

## Behavioral data

### PSE

### RT

## Task-related pupillary change

## Baseline pupil size (1s ahead of bar moving)

## gaze heat map

## Blink

### PSE

The probabilities with which the participants chose ‘ahead’ (i.e., the answer of right for LVF and of left for RVF) were averaged in each SOA (Figure 1B). The average probability of each participant (N= 65) was fit with a psychometric function which implements the maximum-likelihood method. The PSE was estimated by the value with a probability of 0.5. Eight participants’ data were rejected from the statistical analysis due to a failure of the fitting or a large bias of averaged gaze fixation position (> 4.5°). We observed the presence of a flash-lag effect in both visual fields (LVF: (1, 64) = -8.486, = 0, Cohen’s = 1.053, = 1.942764^{9}; RVF: (1, 64) = -6.453, = 0, Cohen’s = 0.8, = 7.405972^{5}). The point of subjective equality (PSE) in each visual field was first bootstrapped 2000 times to estimate the mean and confidence interval (Figure 1C). The lag effect was significantly larger in the LVF than the RVF ((1, 64) = -2.562, = 0.013, Cohen’s = 0.318, = 2.748), consistent with previous studies

### RT

Response times (RTs) were calculated from the time of flash stimulus presentation to the participants’ key presses. We tested second-order polynomials fitting (i.e., a 0) and monotonic fitting (i.e., a = 0) as Models 1 and 2 (see Method) to estimate the relationships between SOA and RTs using a least squares method. The solid lines show the model which more likely well explains the data determined by AIC. A two-way repeated measures ANOVA on the RTs in SOA and VF conditions revealed a significant main effect on SOA ((7, 448) = 6.541, p = 0, = 0.093, = 87.535). RTs at the SOA of -33.3 ms were slower than those of -66.7, -83.3, and 33.3 ms (p < 0.05), consistent with the FLE. Although the FLI in RT seemed larger in the LVF, there were no significant main effect on VF ((1, 64) = 0.105, p = 0.747, = 0.002; = 0.091) or interaction between SOA and VF ((7, 448) = 0.704, p = 0.668, = 0.011, = 0.002).

### Gaze fixation

To assess whether the gaze fixation bias across VFs relates to the FLI anisotropy, we counted gaze fixations and calculated the histograms of x coordinate to compare the gaze bias (Figure 2A). Since participants were requested to fixate the central fixation cross, the histogram should ideally show a normal distribution with an average of center monitor coordinates. However, the distributions in both VFs were skewed toward the VF where the stimulus was presented. However, the median value in gaze displacements within each VFs was not significant, as shown in Figure 2B ((1, 64) = -0.057, = 0.955, Cohen’s = 0.007, = 0.136)), indicating that these small biases in gaze fixations were unlikely to account for the FLI anisotropy.

### Pupil changes in each VFs and lags

Next, we compared the pupillary changes time-locked to the task onset to assess differences across VFs. Figure 3A illustrates the response-locked pupil changes from the baseline period to 2 s after the response across participants and SOA. Phasic pupil dilation was likely associated with the button response in both VF conditions. Figure 3B shows the grand-averaged pupil change across participants after the task response. A Two-way repeated-measures ANOVA on the pupillary changes in SOA and VF conditions revealed a significant main effect of VFs

((1, 64) = 4.625, p = 0.035, = 0.067, = 371.589), indicating that the pupillary changes in the RVF were larger than in the LVF. There was also a significant main effect of SOA ((7, 448) = 4.83, p = 0, = 0.07; = 6.426). However, there was no significant interaction ((7, 448) = 1.192, p = 0.306, = 0.018, = 0.009).

Figure 3C shows the velocity of the pupil change across participants after the task response. This indicates that there were faster changes in returning to the baseline level in the LVF than in the RVF, with marginal significance but relatively strong evidence for H1 from the bayes factor ((1, 64) = 3.073, p = 0.084, = 0.046, = 83.605). However, there were no significant main effect of SOA and its interaction ((5.977, 382.514) = 0.765, p = 0.597, = 0.012; = 0.001; (5.703, 365.01) = 0.652, p = 0.681, = 0.01, = 0).

|  | PDR\_res | vel | BP | gazeBias | pse |
| --- | --- | --- | --- | --- | --- |
| vel | 0.2472 | 1 | - | - | - |
| BP | -0.1068 | 0.0084 | 1 | - | - |
| gazeBias | -0.1998 | -0.3264 | -0.2796 | 1 | - |
| pse | 0.2358 | -0.0183 | 0.0418 | 0.0717 | 1 |
| RT | -0.2772 | 0.3809 | -0.1797 | -0.1475 | -0.1877 |