Correcting video-based eye-tracking signals for pupil size artifacts

Kyoung whan Choe[1], Randolph Blake[1,2] & Sang-Hun Lee[1]

[1]Department of Brain & Cognitive Sciences, Seoul National University, Seoul, Korea

[2]Vanderbilt Vision Research Center & Department of Psychology, Vanderbilt University, Nashville, Tennessee

Cognitive and Systems Neuroscience Lab

Abstract

Video-based eye-tracking relies on locating pupil center to measure gaze positions. Although widely used, the technique is known to generate spurious gaze position shifts up to several degrees in visual angle [1,2], which may lead to erroneous conclusions if they are taken as actual gaze positions. Here, we recorded pupil size and gaze position from 23 observers performing a fixation task and examined their relationship. We found that the pupils contracted as fixation was prolonged, at both small (<16 s) and large (<4 min) time scales, and these pupil contractions were accompanied by systematic errors in gaze position estimation. When pupil size was regressed out, the quality of gaze position measurements was substantially improved. We confirmed the presence of systematic changes in pupil size, again at both micro and macro scales, and its tight relationship with gaze position estimates when observers were engaged in a visual decision-making task [3]. Our results demonstrate that pupil size, which changes dynamically by fixation duration and stimulus/task factors, should be monitored mandatorily and regressed out from video-based gaze position measurements.

Eye-tracking experimental setup

In a dimly lit room, observers viewed the monitor at a distance of 90 cm while their binocular eye positions were sampled at 500 Hz by an infrared eye tracker with 'pupil-corneal reflection (P-CR)' mode.

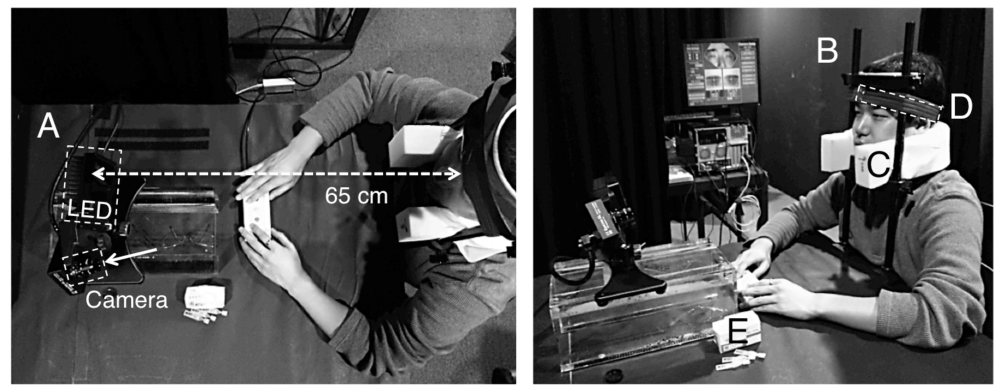
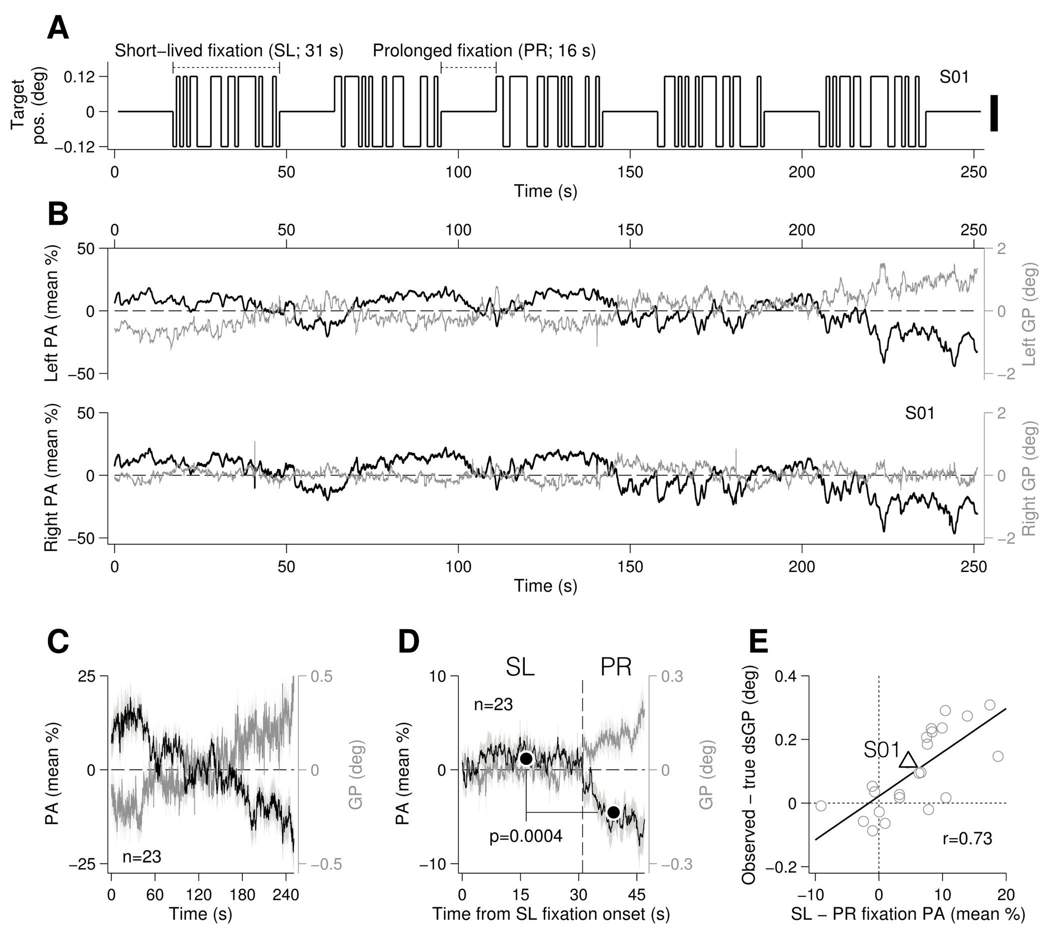


Fig 1. Eye-tracking setup

(A) EyeLink 1000 (SR research)
(B) HeadSpot chin rest (UHCOtech)
(C) 70x9x5 cm memory-form cushion
(D) Head strap (cotton buckle belt)
(E) Disposable artificial tears

* Setup takes about 5 minutes.

Pupil in action: visually guided saccade task



❖ 1 Hz down-sampled GP or PA (dsGP/PA): averaged samples from 0.33–0.67 s (see Fig. 4E)

Fig 2. Relationship between endogenous pupil size changes and gaze position estimates

(A) Observers fixated a small fixation target (diameter 0.12°), the position of which was updated every 1 s. During 'short-lived fixation (SL)' block, the target shifted its position unpredictably between two lateral locations (±0.12°). During 'prolonged fixation (PR)', it stayed at the screen center (0°)
(B) Pupil area (PA) and gaze position (GP) samples during a 251 s run from an representative observer (S01)
(C) PA (averaged across observers) monotonically decreased during a run, reflecting the decreasing level of arousal, and GP was highly anti-correlated
(D) During SL block, PA and GP were stable. During PR block, PA decreased, perhaps reflecting arousal level, and GP deviated from the fixation target (0°)
(E) GP deviation magnitude was highly correlated (p=0.0001) with the PA difference between SL and PR blocks

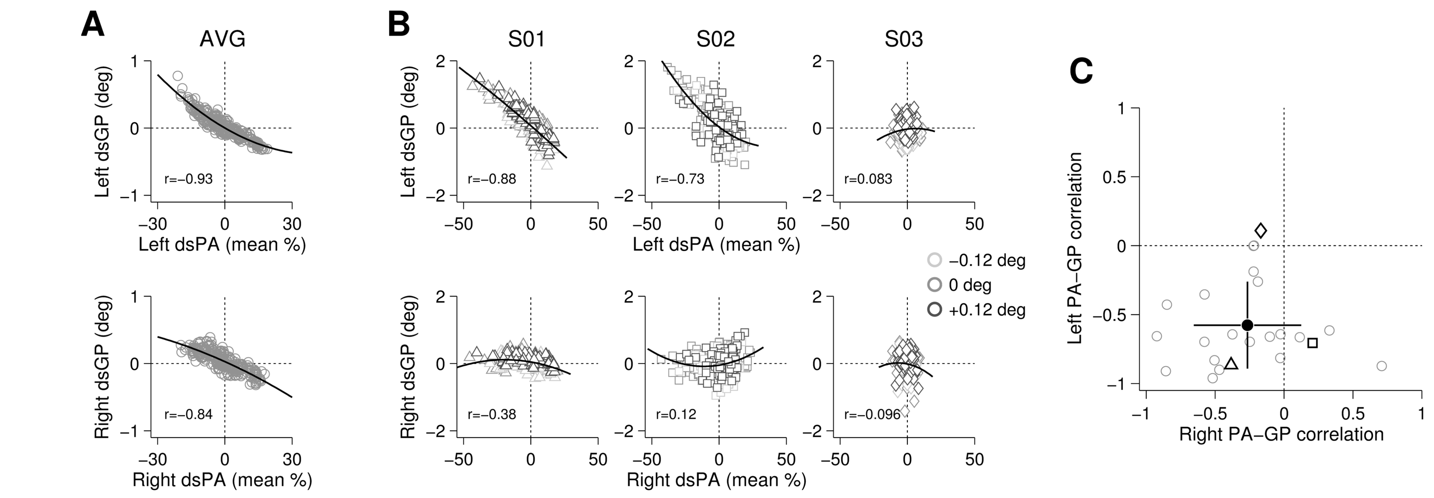


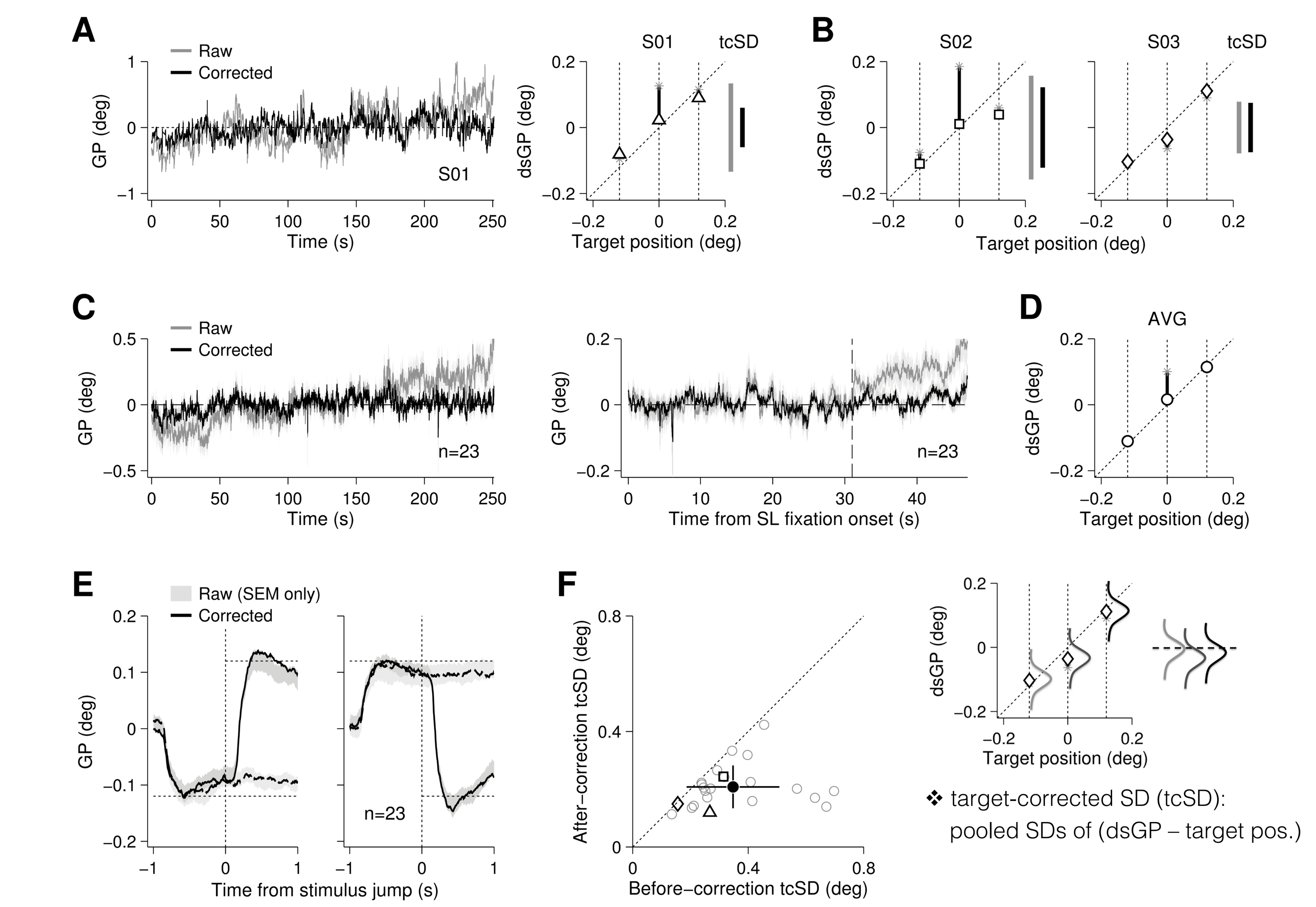
Fig 3. Individual differences and left-eye/right-eye differences in pupil size artifact

(A) PA-GP correlation from the averaged time-course (Fig. 2C): 2nd order polynomials were used to describe PA-GP relationship
(B) Three representative observers (S01-3) with different levels of correlation
(C) Summary of 23 observers. There were large individual differences in PA & GP correlation

Based on these findings, we corrected gaze position estimates for pupil size artifact using 2nd-order polynomial regressor:

$$GP_{corr} = GP - (\alpha + \beta{*}z(PA) + \gamma{*}z(PA)^2)$$

This correction was performed separately for the two eyes and for each individual observer



❖ target-corrected SD (tcSD): pooled SDs of (dsGP – target pos.)

Fig 4. Effects of pupil artifact correction

(A) Comparison of GP and GP_{corr} in S01. GP in PR (target at 0°) required the most correction (Fig. 2D-E). Thanks to correction, tcSD was markedly reduced. (B) S02 is similar to S01. In S03, correction did no harm when there is negligible pupil artifact
(C/D) Comparison of GP and GP_{corr} of the averaged time-course. Most of the artifacts (Fig. 2C-D) were corrected
(E) Saccade trajectory before and after correction. Genuine eye movement signals were preserved despite the correction
(F) tcSD after correction was (0.21° ± 0.07°), comparable to the radius (0.21°) of the sustained fixation span [4]

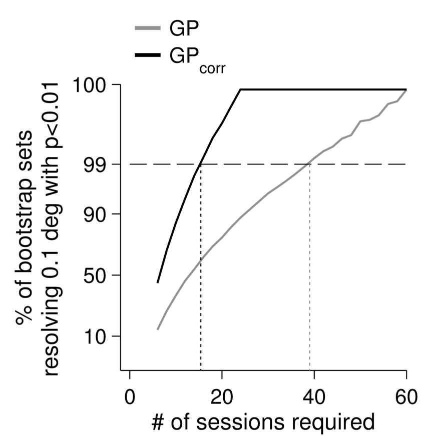


Fig 5. Statistical power analysis for benefit quantification

We estimated how many observations were required to reliably resolve a small difference in gaze position via Monte Carlo simulation. It was assumed that 20 measurements are collected respectively for two fixation positions separated only by 0.1° in a single experimental session. Those two sets were acquired by random sampling from two Gaussian distributions that differed by 0.1° in mean but shared a single specific value of SD, the population tcSD from either GPs or GP_{corr}s. Simulations were carried out by varying the number of experimental sessions, and the statistical power was assessed by how rapidly the percentage of the bootstrap sample experiments (n=10,000) with p<0.01 increased as a function of session number. Based on GPs, at least 39 sessions were needed to achieve desired reliability, whereas only 16 sessions were needed based on the GP_{corr}s

Correction in action: visual decision-making task

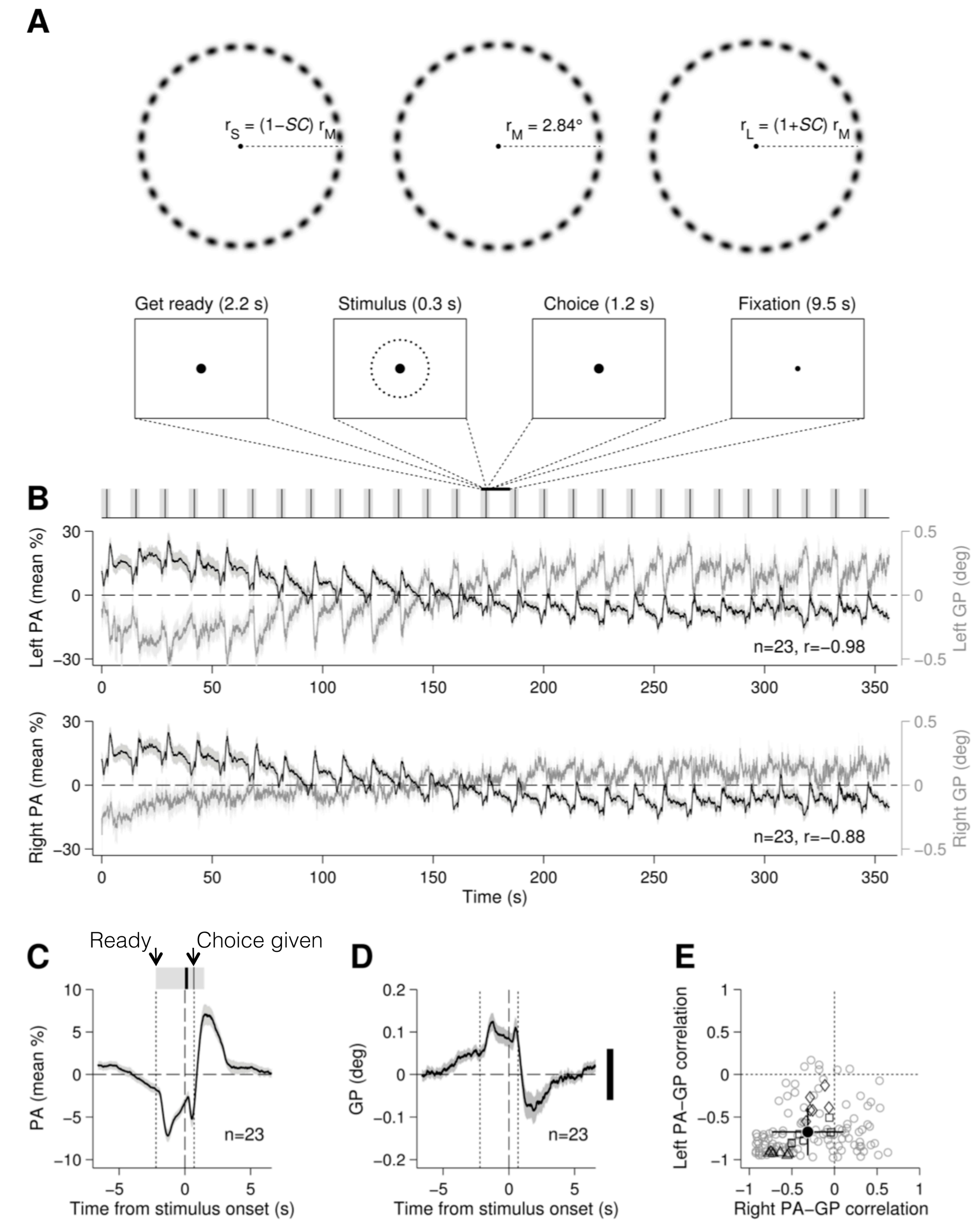


Fig 6. Pupil artifact replication

(A) The same set of observers performed six runs of a fine ring-size discrimination task [3] immediately after Exp 1. They judged the size of briefly presented rings (SC=0.02° ± 0.009°) that appeared periodically. Observers were urged to maintain strict fixation throughout the experiment
(B) PAs and GPs (averaged across runs and observers) during a 356.4 s run. Again, PAs tended to decrease over time, and GPs were highly anti-correlated with PAs, confirming the pupil size artifact
(C) Trial-averaged PA. Pupils constricted in response to the ring stimuli and dilated when observers were expecting a stimulus or were evaluating the choices they made
(D) Trial-averaged GP
(E) Replication of the PA-GP correlation from the different task with more data (recall Fig. 3C)

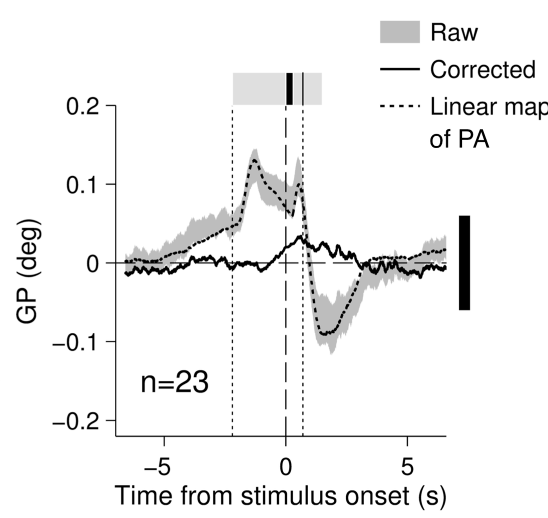


Fig 7. Successful removal of spurious eye-tracking signal associated with task-evoked pupillary responses

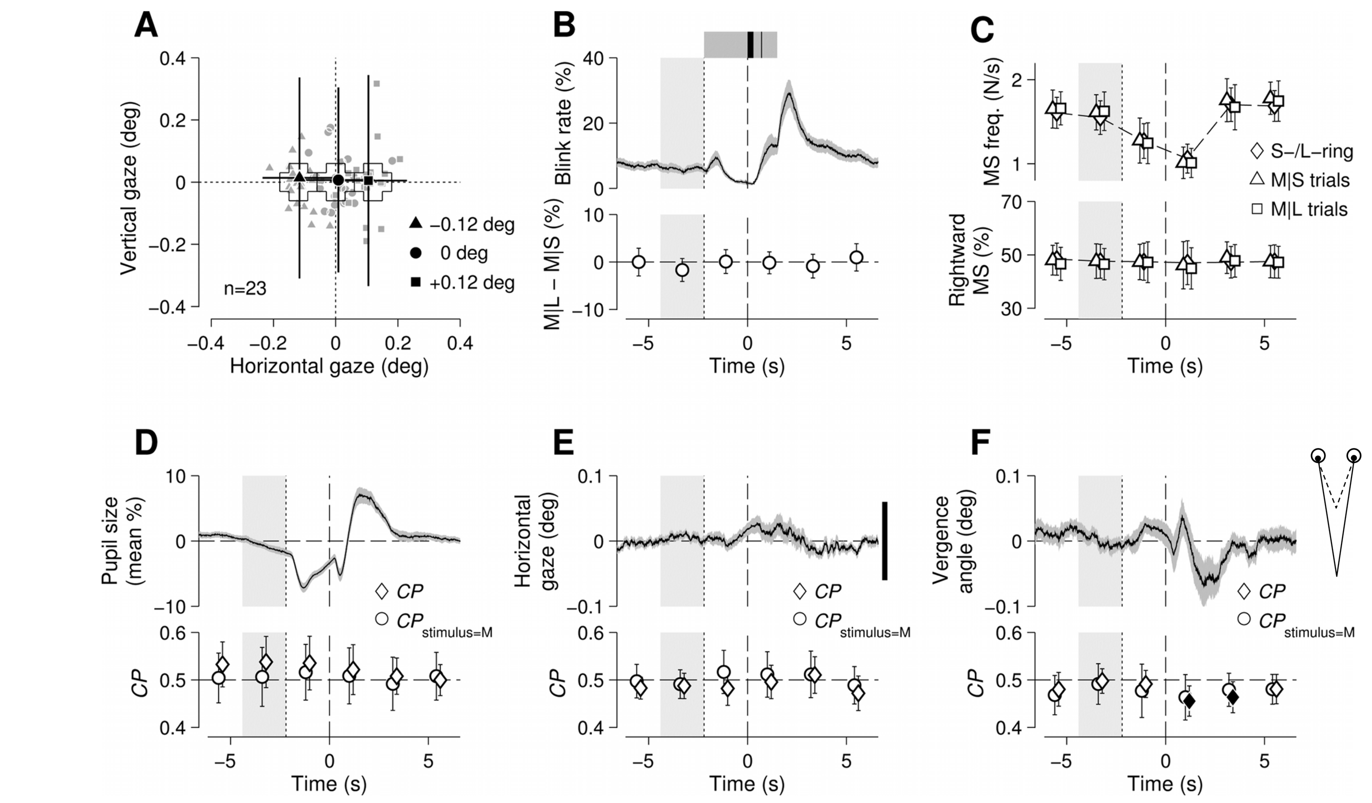


Fig 8. Comprehensive eye movement analyses during decision-making

(A) Accuracy and precision of GPs. Vertical gaze estimation is often unreliable due to pupil occlusion by eyelid. (B) Eye blinks
(C) Microsaccades. Following the ready signal forewarning an upcoming trial, the incidence of microsaccades temporarily dropped, consistent with 'microsaccadic inhibition', then recovered to the baseline following the observers' judgment
(D/E) The same PA & GP as above. The overall GP (corrected) showed only negligible fluctuation inside the fixation target
(F) Divergence of two eyes was greater following 'Large-ring' judgments compared to 'Small-ring' judgments (vergence angle difference at 0-2.2 s = -0.05° ± 0.12°)

❖ For definition of choice probability (*CP*), please see [3] (Choe et al., 2014)

References

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Contacts: Kyoung whan Choe (kywch@snu.ac.kr), Sang-Hun Lee (visionsl@snu.ac.kr)