Figures’ note for N-back ipRGC study

Yuta Suzuki, Shigeki Nakauchi, Hsin-I Liao

10 July, 2025

# Article information

Yuta Suzuki, Shigeki Nakauchi, Hsin-I Liao

NTT Communication Science Laboratories, NTT Corporation, Atsugi 243-0198, Japan

Department of Computer Science and Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka Tempaku, Toyohashi, Aichi 441-8580, Japan

# Results

## Stimulus tuning experiment

### load data

### desription

In order to tune a metameric stimulus which has a higher ipRGC contrast but independent from the cones activities taking into account individual differences in cone distribution (reference), we first identified a metermaric light with high ipRGC light by 2AFC experiment. Figure 2D shows the CIE xy of the candidate low ipRGC light and number of participants in each light that was judged to be regarded as a metameric to the high ipRGC light. In all subjects, the selected light was reported as being perceived as the same color at least once (Supplementary Figure 1). The averaged luminance of selected low ipRGC calculated based upon CIE photoreceptor sensitivities was 708.615 17.355 cd/m2. The averaged Michelson contrast of ipRGC across used metamar pair was 24.757 2.517%.

CIE xy (0.412, 0.241)

## Brightness

### code

### desription

By using the metermaric light in each participants, we confirmed the activation of ipRGC by the brightness judgement experiment. Figure 1E shows the ratio of adjusted luminance to high ipRGC light. The high ipRGC light was perceived around 20% more brighter than the low ipRGC light ((25) = 4.943, < 0.001, = 1.371, > 100), consistent with previous studies (Brown et al., 2012, Yamakawa et al.,2019).

## Pupil size

### load data

### code

### desription

Pupil size was measured using an infrared camera while participants were lighted low and high ipRGC light and engaged in 1- or 2-back task (see Method). Figure 2B illustrates the averaged pupil size during 1- and 2-back task in each lighting condition. A two-way repeated measures ANOVA for the main effect of light showed that the pupil size for high ipRGC light was significantly smaller than for low ipRGC light ((1,25) = 24.214, p < 0.001, = 0.492, > 100), consistent with the previous studies as an effect of activation of ipRGC. Following post analysis also showed that the pupil size in both N-back task for high ipRGC light was smaller than for low ipRGC light (1-back: (25) = -4.81, < 0.001, = -0.641, > 100; 2-back: (25) = -4.846, < 0.001, = -0.703, > 100). In addition, the pupil size of 2-back task was larger than of 1-back task as reported an effect of cognitive load differences previously ((1,25) = 14.702, = 0.001, = 0.37, = 1.034), as reported here and elsewhere.

## Accuracy

### load data

### desription

To see the effect of light on the task performance of N-back task, we compared the hit rate between the lighting condition as illustrated in Figure 2C. We found the main effect of light showing that the the hit rate under high ipRGC was higher than under low ipRGC ((1,25) = 4.848, = 0.037, = 0.162, = 0.674). There are significant of interaction between N-back and light condition ((1,25) = 5.239, = 0.031, = 0.173, = 0.686). Post analysis showed that the higher accuracy under high ipRGC was seen in the 2-back but not in the 1-back (1-back;(25) = 0.702, = 0.489, = 0.078, = 0.259, 2-back;(25) = 2.717, = 0.012, = 0.507, = 4.109). As an effect of working memory load on accuracy, the hit rate of 1-back task is higher than of 2-back task ((1,25) = 30.806, p < 0.001, = 0.552, > 100). The False alarm also decreased in the 2-back task under high ipRGC with marginaly significance ((25) = 1.914, = 0.067, = 0.421, = 1.003). The details of hit, miss, false alarm and correct rejection are shown in Tables S1.

## Response times

### load data

### code

### desription

Response time (RT) was calculated from the stimulus onset to the participants’ key presses. Linear mixed model analyses were conducted corresponds to the following formula: . To statistically assess whether the RTs differed between lighting conditions, 95% confidence intervals (CI) for the RTs were estimated with 10000 bootstrap samples. The estimated CIs of RTs between low and high ipRGC was [-28.25, -9.044], (25) = 4.536, < 0.001, = 0.139 for 1-back and [-18.739, 10.804], (25) = 0.355, =0.722, = 0.011 for 2-back shown at top in Figure2D. The RTs was significantly faster for high ipRGC light for both 1- and 2-back task.

## Questionnaire

### load data

### corr sleepiness x fatigue for each sub

### sleepiness x fatigue for each run (no run corrected)

### comparison between lighting orders

### sleepiness x fatigue for each run (regressedout run effect)

### desription

To test whether the light condition affected participants’ sleepiness and fatigue, we asked participants to rate their subjective sleepiness and fatigue on a scale of 0-10. The fixed effects of light, run, and their interaction model including block order are reported here; we fitted the rating scores with light, run, and block order as within-subject factors and subject as a between-subject factor. The block order refers to whether the high ipRGC block or low ipRGC block was performed in the first block. The scores were negatively affected by the light condition, indicating that the high ipRGC light contributed to a lower subjective score for both sleepiness and fatigue (sleepiness: (25) = -2.157, =0.032, = 0.263; fatigue: (25) = -4.602, < 0.001, = 0.562).

To examine whether pupil size could be attributed to variations in subjective fatigue and sleepiness, we computed correlations between pupil size and these subjective ratings. As shown in Supplementary Figure S2, we observed a significant correlation between pupil size and fatigue ratings, but not with sleepiness. Additionally, we confirmed that the degree of pupil constriction under high-ipRGC light was not predictive of the individual brightness adjustment values in the brightness-matching experiment.

We fitted the rating scores with run and participants as a random effect using a linear mixed model, showing that the subjective sleepiness and fatigue scores increased significantly with an increasing effect of time-on-task (sleepiness: (25) = 8.895, < 0.001, = 1.079; fatigue: (25) = 8.709, < 0.001, = 1.057).

### pupil time course and phasic response

### regress out the effect of time-on-task

## Phasic pupil response

# Supplementary Figure

## Table for hit, miss, FA and CR

### 1-back

| sdt | low\_ipRGC | high\_ipRGC |
| --- | --- | --- |
| hit(n.s.) | 95.93 ± 7.254 | 96.491 ± 4.977 |
| miss(n.s.) | 0.041 ± 0.073 | 0.035 ± 0.05 |
| FA(n.s.) | 0.325 ± 0.456 | 0.366 ± 0.364 |
| CR(n.s.) | 99.675 ± 0.456 | 99.634 ± 0.364 |

### 2-back

| sdt | low\_ipRGC | high\_ipRGC |
| --- | --- | --- |
| hit(\*) | 88.761 ± 6.381 | 91.718 ± 4.996 |
| miss(\*) | 0.112 ± 0.064 | 0.083 ± 0.05 |
| FA(+) | 1.875 ± 1.403 | 1.373 ± 0.828 |
| CR(+) | 98.125 ± 1.403 | 98.627 ± 0.828 |

### corr Pupil x (sleepiness,fatigue)

### description

To examine whether pupil size could be attributed to variations in subjective fatigue and sleepiness, we computed correlations between pupil size and these subjective ratings. A linear mixed-effects model was used, with pupil size as within-subject factors and subject as a between-subject factor, following the equation: Rating∼pupil size+(1|Subject). We found the fatigue ratings, but not sleepiness ratings, were significantly correlated with pupil size (fatigue: (25) = 3.03, =0.003, = 0.248; sleepiness: (25) = 0.142, =0.887, = 0.012).

In addition, brightness adjustment values (i.e., how much brighter the high-ipRGC light appeared) ) could not be explained by pupil size ((25) = -0.19, =0.851, = 0.076). One possible interpretation is that distinct ipRGC subtypes contribute to different functional outcomes[1,2]. For example, M1-type ipRGCs, which primarily project to non-image-forming targets such as the SCN and OPN, may be more directly involved in pupil size. In contrast, non-M1 subtypes are known to project to image-forming regions such as the LGN and are implicated in visuocognitive processing such as brightness enhancement.

# Path analysis

### desription

Using the coefficient of the model, we regressed out the time-on-task effect from the rating scores as shown in Figure 3A. To determine how the light condition, the hit rate, sleepiness, and fatigue affected each other, we performed a mediation analysis as shown in Figure 3B. We found the light condition significantly affected hit rate, sleepiness, and fatigue (hit rate: = 0.083, = 0.044, = 0.165; sleepiness: = -0.089, = 0.029, = 0.179; fatigue: = -0.156, = 0, = 0.316). Although sleepiness negatively affected the hit rate with a weak effect (i.e., lower sleepiness improved the hit rate), we did not find strong evidence that the sleepiness and fatigue rating can explain the hit rate (sleepiness: = -0.077, = 0.075, = 0.145; fatigue: = 0.049, = 0.266, = 0.091 )

## plot model sleepiness and fatigue

### corr

# Figure