Measurements of Contrast Detection Thresholds for Peripheral Vision Using Non-flashing Stimuli

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Abstract. In this work the change of the contrast detection threshold with eccentricity were measured for a range of eccentricities from 0 to 27°. A common approach used for such measurements is to display a flashing stimulus presented by a fraction of a second in the observer's peripheral viewing area. This condition prevents the registration of the results after unintended moving the eyes towards the stimulus and lowering the recorded thresholds. In contrast to this methodology, our stimuli are not modulated over time. We display stimuli continuously and use eye tracker to control the observers' gaze direction. We prove that results of the psychophysical experiments based on this approach are consistent with the previous work.

Keywords: Contrast detection thresholds · Gaze-dependent contrast thresholds · Gaze-contingent display · Gaze-dependent rendering · Eye tracking · Psychophysical experiments

1 Introduction

Our sensitivity to contrasts is reduced with the eccentricity, i.e. with the angular distance from the gaze direction [12]. Models of this feature of human vision are developed based on the data from psychophysical experiments, in which stimuli is presented to observers in her/his peripheral vision for a short time on the order of milliseconds [2,7–11]. Flashing the stimuli ensures that observers do not turn their eyes toward the stimuli and, in this way, unintentionally increase the sensitivity. However, such condition is unlikely to be found in typical viewing scenarios, because natural scenes do not flash. Even moving object are presented to viewers for longer time in a continuous manner. Another evidence of the drawback of this methodology is that in the different studies, the absolute values of contrast detection thresholds varied substantially among these studies [8]. The most likely reason of this effect appears to be different flash duration used in various experiments [8].

In this work, we conduct a similar psychophysical experiment but using non-flashing stimuli. The contrast detection threshold is measured for a number of the eccentricities ranging from 0 to 27°. We created sin-grating stimulus of a

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2 cpd (cycles-per-degree), which was continuously displayed on the screen in the horizontal or vertical orientation. Observers were asked to look straight to the marker and judge the orientation of stimulus seen in their peripheral vision. This condition is unnatural for humans, because we instinctively look away in the direction of the observed object. Therefore, we used eye tracker to test whether the observers changed their viewing direction. If such condition is detected, the stimulus was cleared and then redrawn with a random orientation.

We test the effectiveness of this methodology by performing a case study, in which the orientation of the stimulus is not changed after changing the viewing direction. Under such conditions sensitivity to contrasts should be higher, because observes could see the stimulus in the foveal vision for a short time before it was cleared. The obtained results revealed this relationship between these two experimental methodologies.

In Sect. 2 we review previous work related to the gaze-dependent contrast detection threshold measurements. In Sect. 3 the details of the conducted experiments are presented. We discuss the achieved results in Sect. 4.

2 Previous Work

The peripheral contrast detection thresholds have been measured in a number of studies. Robson and Graham [10] used 4 cycles patches of horizontal grating. This stimulus was displayed for 100 ms. Cannon [2] used vertical sin-grating patches presented to the right of fixation for 2 s, including 350 ms rise and fall times. Thomas [11] used a patch presented for 1 s, either with an abrupt onset and offset or ramped on and off over the whole second. Pointer and Hess [9] presented horizontally oriented sinusoidal grating patches in Gaussian envelopes. This stimuli were displayed for 250 ms using the Gaussian window with the temporal spread. Mullen [7] measured the detection threshold for chromatic stimuli. The sin-grated patch was displayed continuously. The results show that at each spatial frequency color contrast sensitivity declines with eccentricity approximately twice as steeply as luminance contrast sensitivity.

Our approach is inspired in particular by Peli et al. [8]. They measured the threshold contrast required for discrimination between horizontal and vertical sinusoidal grating patches (Gabor functions). Measurements were taken at the fovea and at temporal eccentricities of 2.5, 5.1, 10.3, and 22.8°. Thresholds at each eccentricity were measured for five spatial frequencies, 1, 2, 4, 8, and 16 cpd. Stimuli contained about 4 cycles, but only approximately two cycles were visible because of the rapid decline of the Gaussian envelope. The background luminance was equal to 37.5 cd/m^2. The stimulus was presented for 0.5 s with an abrupt onset and offset.

3 Experiment Design

3.1 Stimuli

In our experiment the stimuli consisted of vertical or horizontal sine-gratings attenuated by a Gaussian envelope (see Fig. 1). To render stimuli, we used the

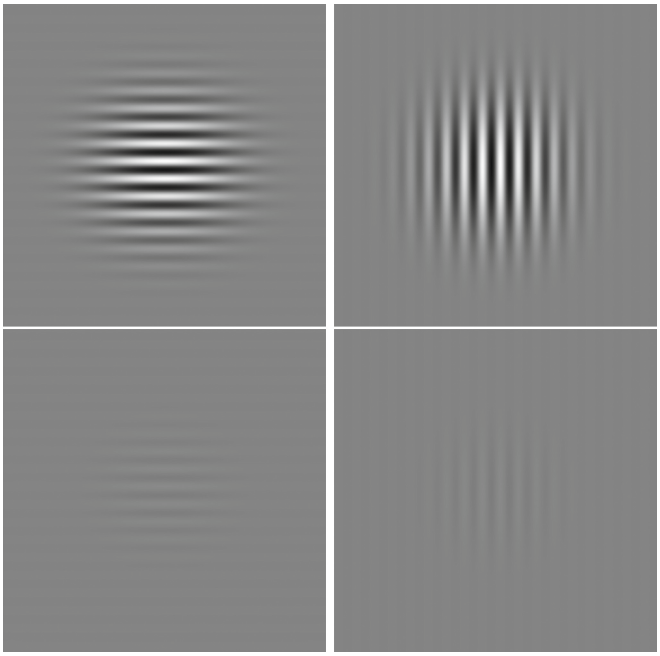

Fig. 1. Examples of the horizontal (left) and vertical (right) sin-gratings used in our experiments. The contrast of the stimuli was reduced from $logC_{10} = 0.3$ (top row) to $log_{10}C = -1$ (bottom row). In our experimental setup, frequency of each stimulus is equal to 2 cpd.

CreateProceduralGabor() function from the Psychtoolbox package[1], which is a Matlab toolbox for creating psychophysical experiments [1]. This function allows to specify Michelson contrast: $c = (I_{max} - I_{min})/(I_{max} + I_{min})$, where I_{max} and I_{min} correspond to maximum and minimum luminance of the Gabor patch, respectively. We report all data in terms of threshold contrast C, which is a relative modulation of the sine-grating: $C = c * L_b/L_{max}$, where L_b is the luminance of the background and L_{max} is the maximum luminance of the display.

We set the background luminance L_b to 60 cd/m^2, when L_{max} was equal to 120 cd/m^2. The luminance levels of the Gabor pattern were selected to avoid luminance levels lower than 1 cd/m^2 and higher than 120 cd/m^2, at which the display calibration was unreliable.

3.2 Display

The experiment were run using Sony PVM-A250 TRIMASTER EL, 1920×1080 pixel resolution, high quality reference OLED display. It offers good luminance reproduction with a 10-bit OLED panel. This bit-depth resolution is necessary

[1] http://docs.psychtoolbox.org/CreateProceduralGabor.

for near-threshold detection experiments, in which perceivable spatial resolution is measured. We used the native display calibration to sRGB color profile. Correctness of the calibration was confirmed using the Minolta CS-100A luminance meter.

3.3 Procedure

During experiment the stimuli were observed from a fixed distance of 90 cm, which gave an angular resolution of 57 pixels per visual degree.

The experimental procedure is presented in Fig. 2. Observer was sitting in the front of the green cross marker presented in Fig. 2a. She/he was asked to look at this marker plotted on the grey background. The Gaussian noise followed by the sin-grating has been drawn on the left side of the screen in an arbitrary angular direction. Observer task was to recognize the horizontal or vertical direction of the sin-grating by pressing the *up* or *right* keys on the custom-built control panel. If observer looks away from the marker, it's color turned to red and the sin-grating was cleared from the screen (Fig. 2b). The stimulus was redrawn in randomly chosen orientation, when observer began to look at the marker again (Fig. 2c). We captured the gaze direction using 60 Hz eye tracker (remote EyeTribe device with average accuracy of 0.5°) [14]. We set the acceptable deviation from the desired viewing direction to 2°, i.e. for lager deviation the stimulus was hidden.

The procedure was repeated for eccentricities of 5, 10, 15, 20, and 27°. We also measured sensitivity at fovea (i.e. eccentricity equal to 0°).

Fig. 2. Screenshots from our experiment. Green (or red) cross points out the desired viewing direction. The blue square depicts the gaze location captured by eye tracker.

To find the threshold magnitude of the sin-grating, we used the QUEST adaptive procedure [13]. The QUEST procedure is based on the assumptions about the distribution of responses near the threshold and an actual shape of the psychometric function [6]. Many trials are repeated while varying the magnitude of the stimulus. The magnitude of a current trial is determined on the basis of the observer's responses in previous trials. In our experiment, the stimuli magnitude was the degree of the contrast in log10 units. QUEST adaptively determines the degree of contrast for the next trial based on the observer's correct or incorrect response for the current trial. We used the QUEST implementation from Psychtoolbox (version 3).

The main assumption of the above procedure is that observer cannot turn the eyes toward stimulus and, in this way, increase her/his sensitivity to contrast by replacing the peripheral vision with the foveal vision. To test this assumption we performed the second experiment, in which orientation of the stimulus was not changed after the eye movement detected by eye tracker. The stimulus was still cleared but after moving the eyes again to the marker, the stimulus was redrawn in the same orientation. This modification allowed for looking at the stimulus for smaller eccentricity, which, of course, was inconsistent with the objectives of the experiment.

Our eye tracker needed about 17 ms to capture the gaze direction. Another 17–33 ms was consumed by the 60 Hz display to clear the image to the background gray and display the stimulus. This latency was enough to turn the eyes and see the stimulus even for the largest eccentricity of 27° [3]. This effect was significant in the case study without the orientation modification. However, it did not affect the results in the actual experiment with the random orientation modification.

3.4 Participants

We asked 6 volunteer observers to conduct the experiment (age between 21 and 47 years, average age 27.67, 2 females, 4 males). While there were no time limitations to our study, the average observer finished the experiment in approximately 10 min. Observers declared normal or corrected to normal vision and correct colour vision. Before the experiment we briefly described to each participant the motivation behind the detection threshold measurement but not the details of our strategy. In particular, they did not know if the stimulus orientation was changed after unintended gaze relocation, i.e. they did not know whether it was the case study or the actual experiment.

4 Results

The goal of our experiments was to measure the contrast detection threshold for the peripheral vision using the non-flashing stimuli. We also compare the achieved results with the contrast discrimination model reported in the literature.

4.1 Detection Threshold

The blue plot in Fig. 3 presents results of our experiment (the threshold values averaged over all observers are additionally depicted in Table 1). The contrast detection threshold for the foveal vision (zero eccentricity) is equal to $C = 0.013$, which can be expressed as the sensitivity $S = 1/C = 76.92$ or $log_{10}S = 1.89$. This sensitivity is comparable with the sensitivity for 2 deg stimuli and 60 cd/m^2 background luminance reported in the literature (in the recent studies Kim et al. [4]

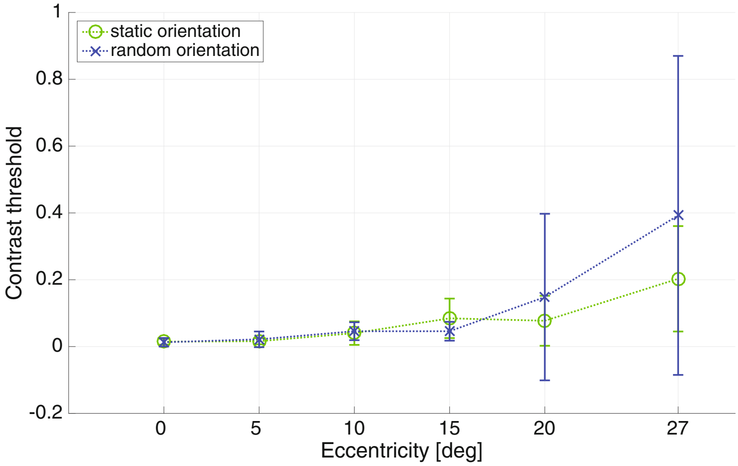

Fig. 3. Contrast detection thresholds for 2 cpd stimuli averaged over all observers. Error bars depict the standard deviation of the measurements.

Table 1. Statistics from the contrast detection experiments.

Eccentricity [deg]	0	5	10	15	20	27
Random orientation [log10 units]						
Detection threshold	0.013	0.022	0.046	0.046	0.148	0.393
Standard deviation	0.013	0.023	0.027	0.028	0.249	0.477
Minimum value	0.002	0.005	0.012	0.028	0.041	0.049
Maximum value	0.038	0.071	0.082	0.107	0.712	1.162
Static orientation [log10 units]						
Detection threshold	0.016	0.014	0.036	0.079	0.074	0.181
Standard deviation	0.009	0.009	0.035	0.059	0.075	0.159
Minimum value	0.005	0.004	0.009	0.02	0.022	0.044
Maximum value	0.028	0.034	0.115	0.159	0.235	0.455
Threshold difference [log10 units]:	−0.003	0.008	0.010	−0.033	0.074	0.212

report a value of $log_{10}S = 1.5$). The thresholds slightly increase for small eccentricity from 5 to 15° but they are clearly higher for 20 and 27°. As it was expected the thresholds are growing exponentially.

The green plot in Fig. 3 shows the results of the experiment in which orientation of the stimulus was not changed after detection of the observer's eyes movement. As can be seen the threshold values for eccentricities of 20° and 27° are clearly lower than thresholds measured in the previous experiment. It indicates that eye tracker plays crucial role in the experimental methodology.

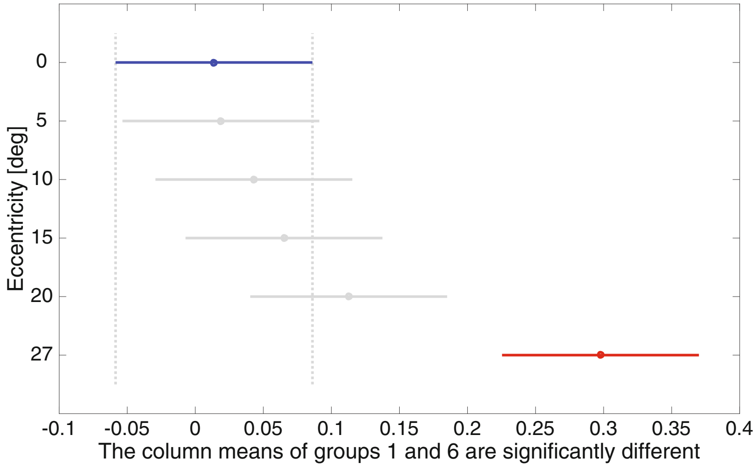

Fig. 4. The pairwise comparison results from ANOVA revealing a statistically significant difference between the results of the experiment with static and randomly modified orientation of the stimulus. The mean contrast threshold for each eccentricity is represented by a dot, and the confidence interval is represented by a line extending out from this dot. Two means for different eccentricities are significantly different if their intervals are disjoint.

A 2-way analysis of variance (ANOVA) was used to gauge the statistical difference between both experiments. The dependent variable was the measured contrast thresholds. The independent variables were experiment type (static or random orientation) and eccentricity. ANOVA reveals a statistically significant main effect of eccentricity ($p = 0, F = 9.77$), experiment type ($p = 0.0012, F = 4.57$), and interaction between eccentricity and experiment type ($p = 0.0207, F = 1.98$). In Fig. 4 the confidence intervals for measured eccentricities are presented. The plot depicts that results achieved in the experiments are significantly different for eccentricity of 27°.

4.2 Model

As it has been justified in Peli et al. [8], it is difficult to directly compare the results of the peripheral contrast threshold measurement experiments because of a bias introduced by the experimental condition (e.g. different flash time). For this reason, following methodology presented in Peli et al., we fit the model of the contrast constancy based on our experimental results and then compare this model to model presented in the literature. As a reference model we chose results from Peli et al. because in this work there is a comparison of the different studies on the peripheral contrast detection thresholds indicating that the model is valid against other studies.

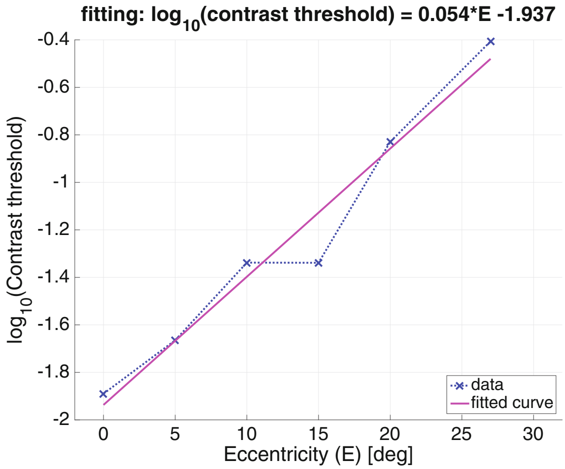

Fig. 5. Averaged contrast threshold plotted on the logarithmic scale. The magenta line shows fitting of the measured data based on the linear polynomial.

The *contrast constancy* holds for a wide range of frequencies, suggesting that sensitivity is constant across the spectrum at superthreshold [5]. However, lower-contrast features could disappear when their contrast is below the threshold level, when the object moves e.g. to the observer. Some mechanism must exist in the Human Visual System (HVS) to compensate for this effect, because these changes from visible to invisible, would affect the perception of images more than the variations in contrast at suprathreshold levels. When an object moves closer to the observer, the spatial frequency of various features in the object decreases. At the same time, the overall size of the object's retinal image increases. Therefore many of these features now can fall on retinal areas farther from the fovea, where contrast sensitivity is lower. Thus, the requirements for invariance could be satisfied if contrast thresholds were to vary as the product of the spatial frequency and the retinal eccentricity.

On a logarithmic scale the threshold varies linearly with the eccentricity (see Fig. 5). If we want features stay invariant with distance changes, the thresholds should be related to the eccentricity in a specific way:

$$log_{10}C = m * E + b, \tag{1}$$

defined by the values of m and b parameters. Especially, the slope of the line (m) is important because b (contrast threshold at eccenticity of $0°$) can vary depending on the stimuli and experimental procedure [8].

In Fig. 5 we fitted our experimental data to this model (magenta line). In Fig. 6 our fitting is compared with the data from Peli's orientation identification experiment [8]. We shifted the lines along the Y axis to $b = 0$ to obtain the visually consistent plots (and compensate the experimental bias). As can be seen in the plot our model (magenta line) matches results from Peli et al.

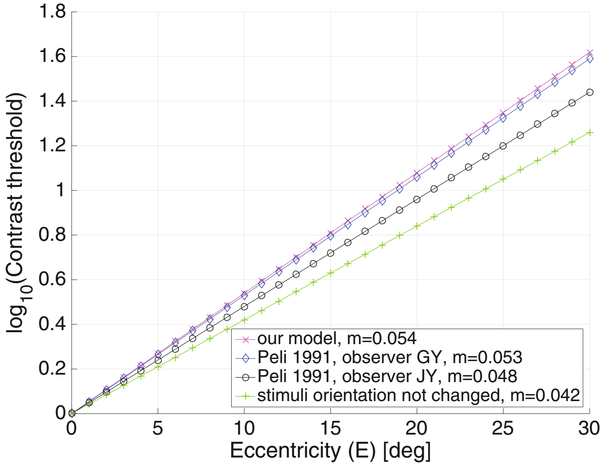

Fig. 6. Eccentricity-dependent contrast constancy model for 2 cpd stimulus obtained from Peli et al. 1991 [8] (blue and black lines) and our experiment (magenta line). The green line shows model for test experiment, in which stimuli orientation was not modified after eye movement.

(blue line) for observer GY. The difference between the m coefficients is equal to 0.001. Taking into account the average value for both GY and JY observers, this difference is equal to 0.0035.

5 Conclusions and Future Work

To capture the effect of eccentricity on contrast detection, new contrast threshold detection measurements were conducted using the non-flashing stimuli and eye tracker. The goal was to verify whether the results of such methodology are consistent with the previous works, in which the stimulus was presented in the periphery of vision for a short time. Both methodologies (with flashing stimuli and with eye tracker) prevent the registration of the results after unintended moving the eyes, however, our solution is more natural for typical viewing conditions. The results achieved in the preliminary studies for 2 cpd stimuli are consistent with the results reported in the previous work.

In future work we plan to measure the thresholds for a wider range of the stimuli frequencies, further periphery, and for chromatic stimuli. We also plan to replace the Gabor pattern with the complex stimuli in the form of the renderings of the three dimensional objects. These measurements should be more reliable than the experiments with flashing stimuli that introduce the measurement bias. We expect that better models of the peripheral contrast threshold detection are possible to achieve, especially for the mentioned complex stimuli, for which sufficient observation time is crucial for near-threshold contrast detection [3].

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