Paper

Measurement for the Panum's Fusional Area in Retinal Fovea Using a Three-Dimension Display Device

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ABSTRACT

The limits of Panum's fusional area have been studied by many research groups. Those studies, however, focused only on the measuring direction of horizontal and vertical meridian. In this study, a new experimental method was employed by using a three-dimension display device to fully measure the limits of Panum's fusional area in eight different directions from 0 degree to 360 degrees with a step of 45 degrees in the retinal fovea. The following results were obtained: (1) the horizontal limit of Panum's fusional area in fovea is larger than the vertical limit; (2) the limits of Panum's fusional area are almost symmetrical about the horizontal meridian; (3) the limits of Panum's fusional area are not symmetrical about the vertical meridian; the nasalward limits are obviously larger than the temporalward limits; (4) the form of Panum's fusional area in retinal fovea is suggested to be an off-centered ellipse instead of a standard ellipse reported in previous works.

KEYWORDS: binocular vision, Panum's fusional area, disparity, three-dimension display, retinal fovea

1. Introduction

Before Panum[1] suggested that a retinal point in one eye could correspond with a retinal area instead of point in the other eye, singleness of vision with two eyes was explained by the theory of corresponding retinal points. Any point in the retina of one eye was supposed to have a corresponding point in the retina of the other eye, so that the simultaneous stimulation of any pair of corresponding points in the retinas would present a single perceived image. Furthermore, it was considered that an object which was stimulated by the non-corresponding disparate retinal points would be seen as double. This retinal area of correspondence representing the total amount of disparity compatible with single vision discovered by Panum was known as a "Panum's fusional area".

Since then, the limits of Panum's fusional area have been determined by many studies. The limit of horizontal and vertical meridian was frequently studied[2)-4)]. Furthermore, the fusional area has been shown in most investigations to be much smaller in the vertical meridian than in the horizontal meridian. Because of this meridional difference, it has been suggested that the Panum's fusional area has the form of an ellipse. However, the limits of Panum's fusional area in the other oblique directions, such as 45, 135, 315 degrees etc., were seldom measured except that Fender and Julesz[3] determined the fusional limit of the Panum's area in 45 degrees direction in retinal fovea. The reason, the most previous experiments focused on the direction of horizontal and vertical meridian but not oblique direction, was likely due to their experimental methods. Actual physical stimuli were used in previous experiments, so it was difficult to accurately alter those stimulus targets to any position in retina. Nevertheless, in the present study a constant stimuli method was used to measure the limits of Panum's fusional area by employing three-dimension display device and computer software control system. Because of the convenience of controlling the three-dimension display device by a computer, we created a pair of virtual monocular stimulus targets on the three-dimension display to perceive a binocular view and controlled some parameters of these stimuli, such as the shape, size, position, movement direction, color and etc. Therefore, it is possible to fully measure the limits of Panum's fusional area in any direction and in any position in retina.

The purpose of this study was to fully measure the limits of the Panum's fusional area in eight different directions from 0 degree to 360 degrees with a step of 45 degrees in retinal fovea, in addition to the traditional horizontal and vertical meridian studied previously. The characteristics of the fusional limits in different directions at central retinal fovea were analyzed in a more quantitative level, compared to previous studies.

2. Method

2.1 Apparatus and stimuli

In the present experiment, a three-dimension display device (SANYO THD-10P3, resolution 640×480, refresh rate 60 Hz) was employed to present experimental stimuli dichoptically, i.e. one to each eye for subject. As shown in figure 1, subject seating in front of the three-dimension display device was presented dichoptically a left eye view and a right eye view by the optical polarization action of the image splitter installed behind the LCD panel, hence perceived a binocular vision. A computer was used to display the stimuli on the three-dimension display device by a software system made with Visual C++. Otherwise, the distance between the subject and the three-dimension display device was 70cm and a chin-rest and head-rest system was used in the present experiment for fixing the head of subject against sliding.

The stimuli consisted of a pair of stationary white fixation dots and a line stereogram comprising a left and right eye view of a single white line on a black background. As shown in figure 2, the fixation dot subtended a visual angle 48 min of arc; luminance 50cd/m^2; and chromaticity $(x,y)=(0.343,0.410)$. The line target subtended a visual angle 48 min of arc in height and 3 min in width; luminance and chromaticity were same as those of the fixation dot.

2.2 Subjects

Experimental data were obtained from three male subjects aged between 22 and 24 years. All of them were with normal visual acuities and with no oculomotor problem, except subject Y.E. who was myopia corrected by contact lenses.

2.3 Procedure

In the present experiment, the investigation was made using a method of constant stimuli with an exposure time of the stimulus target shorter than the latency period for eye movements in response to a convergence stimulus. This latency period has been found to be 140 ms by Ginsborg[6], 150-200 ms by Westheimer and Mitchell[7], and 160 ms by Rashbass and Westheimer[8]. Therefore, the exposure time of the stimulus target adopted 140 ms in our experiments.

After a subject was adapted to the dark about 15 min, a pair of fixation dots, which were projected into the same position in fovea of left and right retina, were presented for 3 seconds, afterward, the fixation dot was turned off. At the same instant, the stimulus targets appeared and

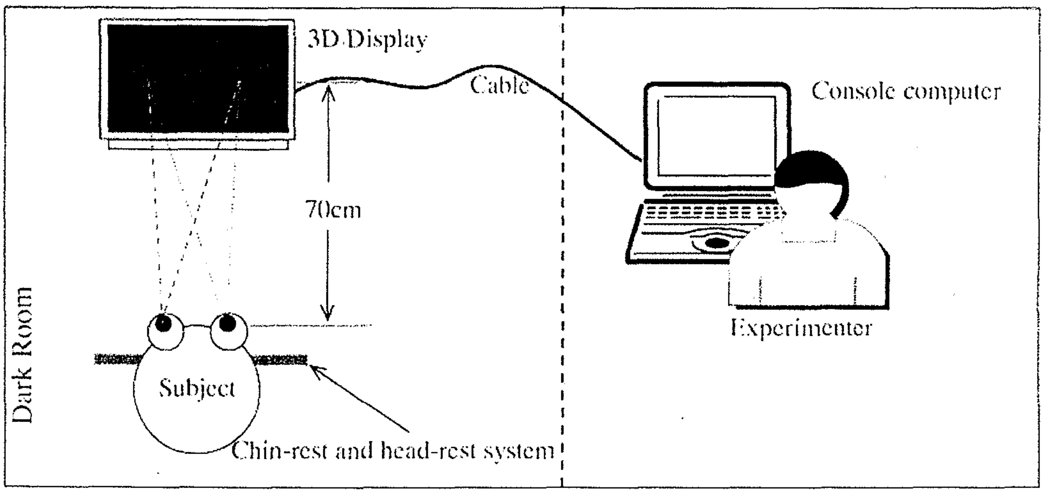


Figure 1 A schematic plan of the experimental apparatus

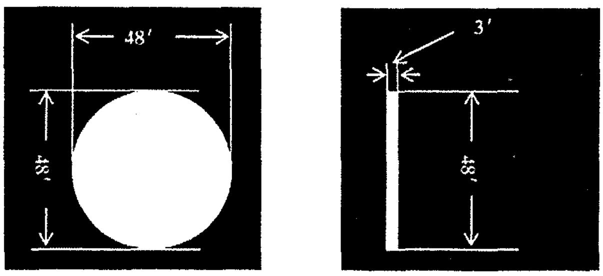


Figure 2 The experimental stimuli comprising a white fixation dot and a white line for each eye in a black background

Table 1 Possible responses in experiment

Category	Percept	Response
A	Fused	1
B	Probably fused	2
C	Not sure	3
D	Probably double	4
E	Double	5

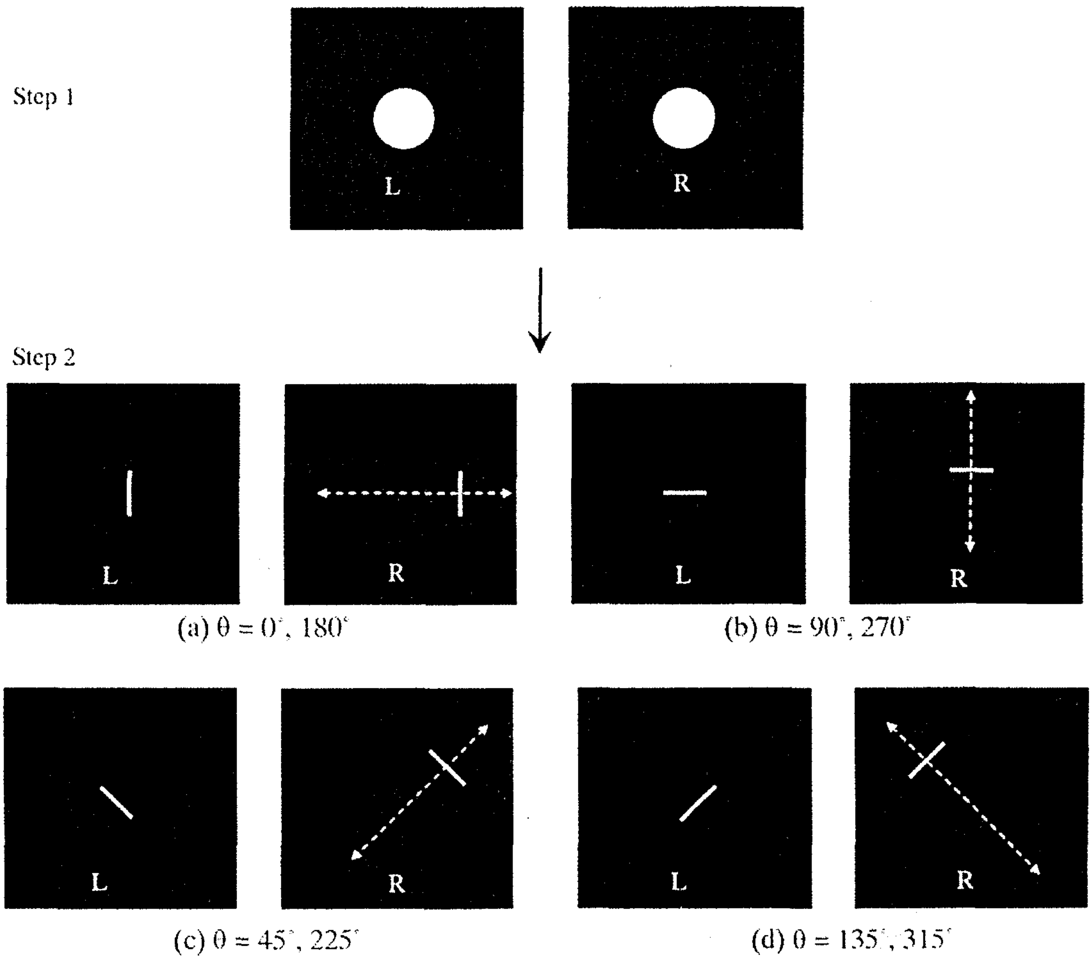


Figure 3 The experiment includes two steps. In step 1 a pair of fixation dots simultaneously appears in the retinal fovea of the left and right eye; in step 2, four experimental conditions (a, b, c, d) in eight different moving directions will be done L: left eye image, R: right eye image, θ : stimulus changing direction.

lasted for 140 ms. Then the subject was instructed to respond as described in Table 1, which also used by Diner and Fender[9)10)]. The experiment was repeated by altering the position of line target in right eye view along a certain angle θ (θ varying from 0 degree to 360 degrees with a step of 45 degrees shown in figure 3) in a random way within a chosen range, while always keeping the line target in the left eye view fixed on the central fovea of left eye, until enough responds had been obtained to gain a better estimate of the threshold. In all experimental conditions, both line stimulus targets in left and right eye view were set to be always perpendicular to the direction of stimulus moving.

Four experimental conditions were obtained in the present experiment as shown in figure 3 (a, b, c, d) by varying the angle θ from 0 degree to 360 degrees with a step of 45 degrees. Each experimental condition was repeated 10 times for each subject.

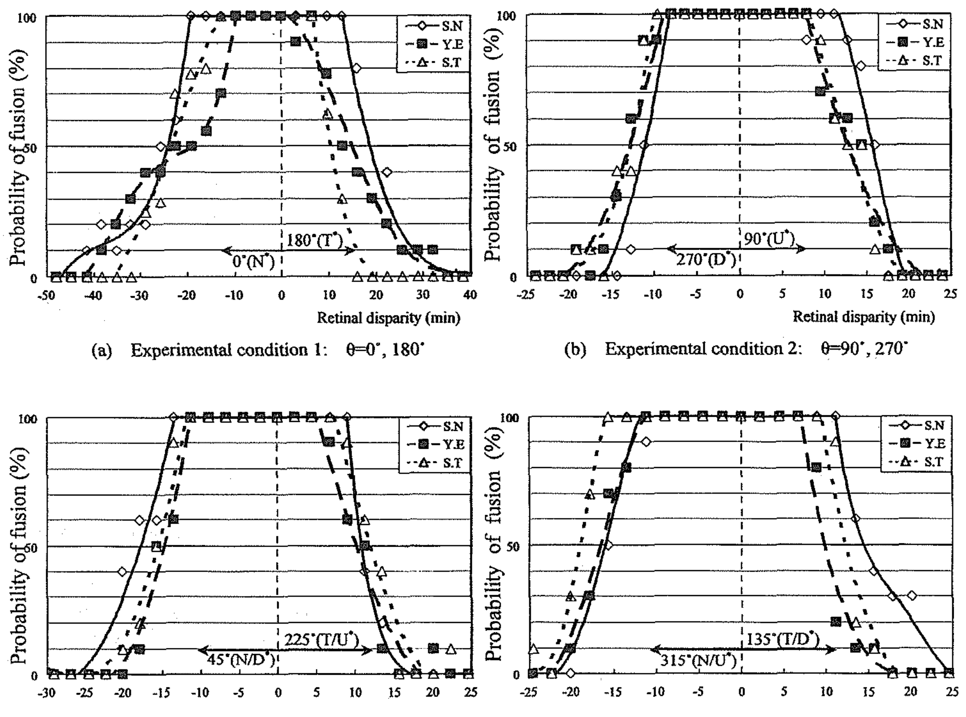
3 Results and Discussion

The probability of fusion at each retinal disparity (p_d) was calculated as follows:

$$P_d = \frac{\text{Total number of reports in categories(A+B)}}{\text{Total number of reports in categories(A+B+D+E)}} \qquad (1)$$

The results of these experiments are shown in figure 4, which display the probability of fusion as function of retinal disparity for each stimulus condition. The values shown in Table 2 were obtained from the results in figure 4 using a 50 percent fusion criterion as a usual specifying threshold. As shown in figure 5, the forms of Panum's fusional area in right retina of three subjects were drawn from the data of Table 2. An average Panum's fusional area in retinal fovea obtained by averaging the data of three subjects was shown in figure 6. In other words, for the present experiment, the line target in left retinal fovea could always fuse into a binocular single vision, with the line target in right retina, if and only if the line target in right retina was fallen within this area, i.e. Panum's fusional area.

In experimental condition 1 (Figure 3. a), the fusional disparity limit of horizontal meridian (0 and 180



(a) Experimental condition 1: θ=0°, 180°

(b) Experimental condition 2: θ=90°, 270°

(c) Experimental condition 3: θ=45°, 225°

(d) Experimental condition 4: θ=135°, 315°

Figure 4 The probability of fusion as a function of retinal disparity (min) for each experimental condition, θ : stimulus changing direction
*The direction based on the retina. (N: Nasalward, T: Temporalward, U: Upward, D: Downward)

degrees) was measured by changing the vertical target line horizontally. The results showed in Table 2 reveal that the nasalward limit is about 22.4-25.6 min of arc and the temporalward limit is about 9.6-16 min of arc, thus the value of Panum's fusional area in the horizontal meridian is about 32-41.6 min of arc. It was noticed that in the present study, the sides of temporal and nasal were based on retina contrary to outside view; so were the sides of upward and downward described later. These values are rather different from some previous results[2)4)]. In fact, not all the previous results are strictly comparable, due to the differences in the experiments techniques, such as the size of the stimulus target, the exposure time of the target, the criterion of threshold and so on. For example, Palmer[2)] quoted a figure of about 25 min with a vertical line subtended 45 min in height, about 15-20 min with a test spot subtended 1.5 min by a 83 percent criterion of threshold. Mitchell[4)] determined this limit to be about 19 min with a vertical 42 min line, which was red in color, by a 50 percent fusion criterion; the illumination of test target was 0.4 mL and exposure time of test target was 120 ms. But we found a new extremely consistent figure from all three subjects that the nasalward fusional limit in retina was significantly larger than the temporalward fusional limit in retina. For example, the limits obtained by subject S.T. under the horizontal meridian condition, were 22.4

Table 2 The limits of Panum's area with eight different directions (using a 50 percent fusion criterion).

Direction	Subject	The limit of fusional area (min) S.N	Y.E	S.T	Average value
0°	N	25.6	22.4	22.4	23.5
180°	T	16	13	9.6	12.9
45°	N/D	17.9	15.6	15.6	16.4
225°	T/U	9	11.2	11.2	10.5
90°	D	16	14.4	14.4	14.9
270°	U	11.2	12.8	11.2	11.7
135°	T/D	13.4	9	11.2	11.2
315°	N/U	15.7	15.7	17.9	16.4

min for nasalward limit and 9.6 min for temporalward limit. This result was mentioned in a previous study[5)] for only one subject, but the author suggested that it was due to the present of fixation disparity. However, in the present experiment, the exposure time of the fixation dots and stimulus targets were controlled carefully. Before the stimulus targets were presented the fixation dots lasted 3 seconds. Under this condition, the subjects had enough time to adjust their eyes to fix the fixation dot accurately. Furthermore, the position of the fixation dot in

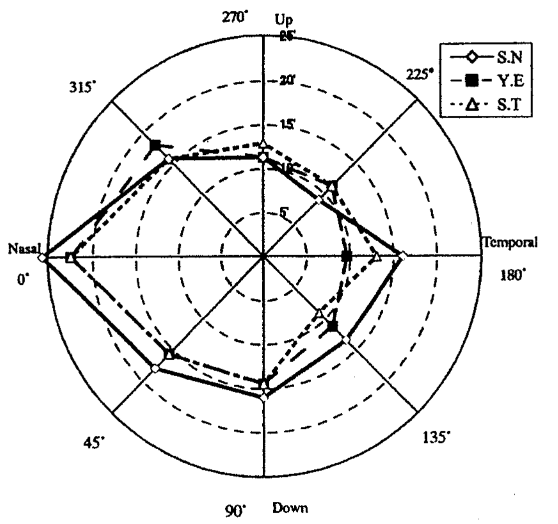


Figure 5 The Panum's fusional areas in right eye retinal fovea from three subjects using a threshold of 50 percent fusion criterion. The directions (temporal, nasal, up and down) were based on retina contrary to outside view

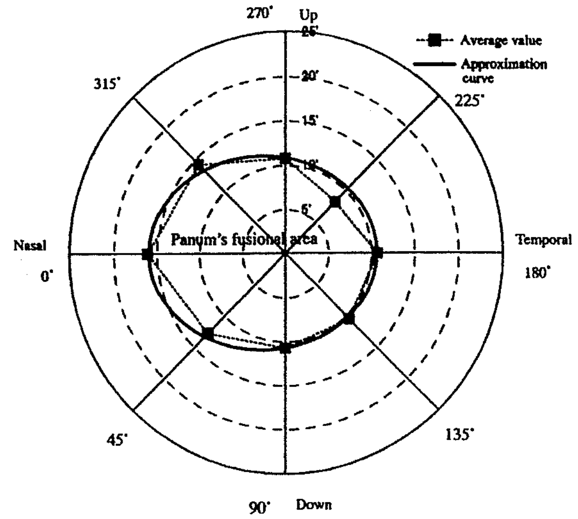


Figure 7 The Panum's fusional area in right retinal fovea, in the form of off-centered ellipse (sold curve), derived from the average data of three subjects using a threshold of 80 percent fusion criterion. The directions (temporal, nasal, up and down) were based on retina contrary to outside view

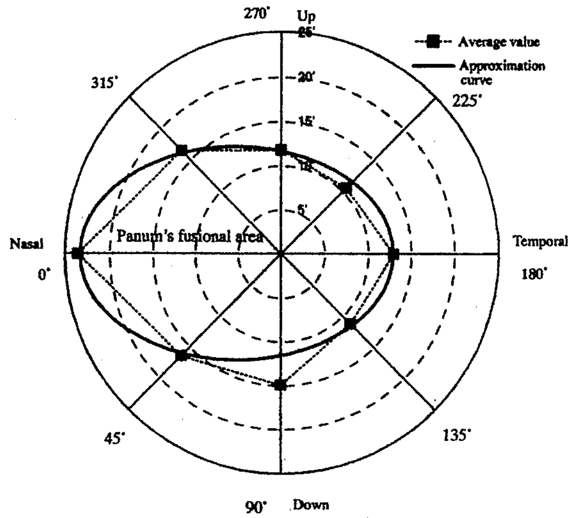


Figure 6 The Panum's fusional area in right retinal fovea, in the form of off-centered ellipse (sold curve), derived from the average data of three subjects using a threshold of 50 percent fusion criterion. The directions (temporal, nasal, up and down) were based on retina contrary to outside view

Table 3 The limits of Panum's area with eight different directions (using an 80 percent fusion criterion)

Direction	Subject	The limit of fusional area (min) S.N	Y.E	S.T	Average value
0°	N	19.6	9.6	19.2	16.0
180°	T	16.0	9.6	6.4	10.7
45°	N/D	13.4	11.2	13.4	12.7
225°	T/U	9.0	6.7	9.0	8.2
90°	D	14.4	8.0	9.6	10.7
270°	U	9.6	11.2	11.2	10.7
135°	T/D	11.2	9.0	11.2	10.5
315°	N/U	13.4	13.4	15.7	14.2

existing the fixation disparity. So, we suggest that the nasalward limit of Panum's fusional area should be essentially larger than the temporalward limit in human retinal fovea, which would be also proved again in the experimental condition 3 (Figure 3. c).

The target lines were then positioned horizontally and moved into vertical disparity in the experimental condition 2 (Figure 3. b), to measure the fusional limit of the vertical meridian (90 and 270 degrees). In comparison with the value of horizontal meridian limit obtained in experimental condition 1, it was easy to find that the vertical limit, about 25.6-27.2 min of arc, was smaller than the horizontal limit, which also has been reported in previous experiments[3)4)]. From all three subjects, it was noticed that the downward fusional limit was slightly larger than the upward fusional limit.

For the experimental condition 3 (Figure 3. c), the target lines were positioned at 135 degrees to the horizontal meridian and separated at 45 degrees to the horizontal meridian, so that the stimulus target was moved nasal-downward (45 degrees) and temporal-upward (225 degrees) in retina. On account of the results obtained in experimental condition 1 and 2, we estimated that the nasal-downward fusional limit should be larger than the temporal-upward fusional limit. It was demonstrated that this expectation was true from the data of experimental condition 3 (Table 2). For example, for subject S.N, the nasal side limit of Panum's fusional area (45 degrees), 17.9 min of arc, was obviously larger than the temporal side limit (225 degrees), 9 min of arc.

Finally, the target line was set at 45 degrees to the horizontal meridian and then moved at 135 degrees to the horizontal meridian in experimental condition 4 (Figure 3. d), so that the target lines were moved temporal-downward (135 degrees) and nasal-upward (315 degrees) in retina. It is a special case, that we couldn't easily estimate which side is larger than the other, like the case of experiment 3, because of the conflict between the different influences of horizontal and vertical separations. However, the results from the experiment indicated that the nasal-upward fusional disparity limit was larger than the temporal-downward disparity limit. This case could possibly be illustrated as the following: in 135 and 315 degrees direction, the influence on the fusional limit from the horizontal meridian might be stronger than from the vertical meridian. It might be due to the influence from the horizontal meridian on the fusional limit is weaker than that from the vertical meridian for a target line moving at a angle approaching the vertical meridian, for example 105 degrees. It is planned to examine this idea in our next study.

From the data shown in Table 2, the comparison between the Panum's fusional limit of 45 and 315 degrees was made to show that the average values of the limit of 45 degrees (16.4min of arc) and 315 degrees (16.4 min of arc) were almost identical; so was in the case of the limit of 135 degrees (11.2 min of arc) and the limit of 225 degrees (10.5 min of arc). So we suggest that the limits of Panum's fusional area are almost symmetrical about the horizontal meridian by neglecting the slight difference of the limit of 90 degrees (14.9 min of arc) and the limit of 270 degrees (11.7 min of arc).

Although, Fender and Julesz[3] had never measured the limits of temporal side, authors assumed the temporal side was symmetrical with nasal side about vertical meridian. So they assumed that the form of Panum's fusional area was a standard ellipse. However, as shown in figure 6 with solid curve, a different form of Panum's fusional area, which is more like an off-centered ellipse instead of a standard ellipse, was obtained. Furthermore, the fusion criterion as a usual specifying threshold was changed into 80 percent so that the new data shown in Table 3 was obtained. An average Panum's fusional area using a threshold of 80 percent fusion criterion was drawn in figure 7. For the threshold of 80 percent fusion criterion, the Panum's fusional area was diminished compared to that of 50 percent fusion criterion; however, both forms of Panum's fusional area in the condition of 50 percent fusion threshold and 80 percent fusion threshold remain similar.

There are some possible factors, which might affect the measurements. The different parameters of stimulus targets, such as the shape, size, position, color and so on could influence the apparent limit of the Panum's fusional area. The different fusion criterions of different subjects were certainly important causes affect the apparent limit of Panum's fusional area. Also, the resolution of the three-dimension display device employed in our experiments was 800 × 640 pixels which could also be a factor affecting the precision of the measurement of Panum's fusional area. Nevertheless, the data of subject Y.E. with myopia corrected by contact lenses showed that the contact lenses do not significantly influence the limits of Panum's fusional area.

4. Conclusions

The results of our study clearly demonstrate that the horizontal disparity limit of fusional area in retinal fovea is the largest (about 32-41 min of arc) and the vertical limit is the smallest (about 25-27 min of arc), which also revealed by many previous studies[1)-3)]. Our study indicates that the limits of Panum's fusional area are almost symmetrical about the horizontal meridian; nevertheless, the limits of Panum's fusional area of nasal side are not symmetrical with the temporal side. The nasalward limits of fusional area are larger than the temporalward limits in retina, which was seldom reported by previous studies. Finally, as shown in figure 6 and 7, the form of Panum's fusional area is suggested rather like an off-centered ellipse than a standard ellipse described by Fender and Julesz[3)].

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