Binocular Disparity Limit in Three-dimensional Display Systems

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In three-dimensional display systems, binocular disparities must be limited within a certain fusional area, called as "Panum's fusional area". Otherwise, too larger or unsuitable disparity could cause double view or serious eye fatigue. The limits of Panum's fusional area have been determined by many studies. The limits of horizontal and vertical meridian were frequently studied. However, the limits of Panum's fusional area in the other oblique directions, such as 45, 135, 225 degrees etc., were seldom measured. Therefore, it is necessary to fully measure the disparity limits of Panum's fusional area in more directions.

In this study, a micro-polariser type three-dimensional display device was employed to present experimental stimuli dichoptically, i.e. one to each eye of subject. The experimental stimuli consisted of a stationary white fixation dot and a white single line for each eye view. The fixation dot subtended a visual angle 48 min of arc; the line target subtended 48 min of arc in height and 3 min in width. Firstly, a pair of fixation dots, which was simultaneously projected into the central fovea of the left and right retina, were presented for 3 seconds, afterward, the fixation dots were turned off. At the same instance, the line targets separated apart were respectively presented to each eye, and lasted for 140 ms. Then the subject was asked to report his or her perception was "single" or "double". As shown in Fig. 1, during the experiment, the line in left eye view was always fixed in the fovea of left eye, while the line in right eye view was changed along a certain angle θ within a certain range in a random way. Sixteen experimental conditions

Fig. 1. (a) The line target in the left eye view was always fixed in the fovea; (b) the line target in the right eye view was changed in a random way

Fig. 2. The Panum's fusional areas in the right retina for three subjects

were obtained by varying the angle θ from 0 degree to 360 degrees by a step of 22.5 degrees.

The results were obtained and the Panum's fusional areas for three subjects were shown in Fig. 2. From the results, we suggest that, in three-dimensional display systems, the horizontal disparity limits about 32-38.4 min and the vertical disparity limits about 19.2-24 min could not be exceeded, otherwise the subject could not obtain a single and comfortable view. In addition, the results reveal that human binocular fusional area in retinal fovea is almost symmetrical about the horizontal meridian. The disparity limits of nasal side and temporal side presented two independent behaviors. In temporal side of retina, the disparity limits have no difference from 90 degrees to 270 degrees. Nevertheless in the nasal side of retina, the disparity limits are found to decrease in a monotonic fashion as measurement direction varying from nasal horizontal meridian (0 degree) to vertical meridian (90 or 270 degrees). Moreover, this study clearly demonstrates that the disparity limits are not symmetrical about vertical meridian, and nasalward limits are larger than temporalward limits.

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In three-dimensional display systems, binocular disparities must be limited within a certain fusional area, called as “Panum’s fusional area”. Otherwise, too larger disparity could cause double view or serious eye fatigue. However, the measurements about Panum’s fusional area in the previous studies focused only on the horizontal and vertical meridian of retina. For fully measuring the Panum’s fusional area in more directions, we took the measurements of the limits of Panum’s fusional area, in sixteen different directions from 0 degree to 360 degrees by a step of 22.5 degrees in the fovea. It was found that the horizontal disparity limit of binocular fusional area is about 32–38.4 min of arc and the vertical limit is about 19.2–24 min of arc. The disparity limits of binocular fusional area are approximately symmetrical about horizontal meridian. However, the disparity limits are not symmetrical about vertical meridian; the nasalward disparity limits are obviously larger than temporalward disparity limits. Moreover, in the nasal side of retina, the disparity limits decrease in a monotonic fashion, and in the temporal side, however, the disparity limits have no obvious difference.

Keywords: Panum’s fusional area, three-dimensional display systems, fovea, binocular disparity

1. Introduction

In recent years, the development of three-dimensional display systems has been the subject of substantial research. Three-dimensional display systems would greatly enhance visualization of video and computer graphics, architectural plans, flight simulations, as well as education and personal entertainment. Among many types of three-dimensional display systems, autostereoscopic systems, such as parallax barrier designs, lenticular element designs and micro-polariser designs, are widely used, because these systems do not require the observer to wear any device, such as glasses, to separate the left and right views, and instead send them directly to correct eye. In these three-dimensional display systems the human visual system perceives depth through binocular disparity cues. In other words, artificial binocular disparities are needed to be created in three-dimensional display systems, so that the observer could obtain stereopsis perception. However, unsuitable artificial disparities cause double view and serious eye fatigue. Therefore, the artificial disparities should be limited within a certain binocular fusional area, which is known as “Panum’s fusional area”.

The limits of Panum’s fusional area have been determined by many studies. The limits of horizontal and vertical meridian were frequently studied^{(1)–(6)}. However the limits of Panum’s fusional area in the other oblique directions, such as 45, 135, 225 degrees etc., were seldom measured, except that Fender and Julesz⁽³⁾ determined

the limit of the Panum’s fusional area at 45 degrees direction to horizontal meridian only in nasal side. Also, Qin et al⁽⁷⁾ determined the binocular disparity limits in eight directions on central vision, and suggested that the form of the binocular fusional area was an ellipse off-centered toward the nasal side on the horizontal meridian. In order to further confirm these results, it is necessary to further measure the disparity limits in more directions. For this reason, in this experiment we aimed to measure the disparity limits of binocular fusional area in sixteen directions from 0 degree to 360 degrees by a step of 22.5 degrees in retinal fovea, so as to provide fundamental data for three-dimensional display systems to present more comfortable view. The experimental method was same with previous experiment⁽⁷⁾.

2. Method

2.1 Apparatus and Stimuli In this experiment, a micro-polariser type three-dimensional display device (SANYO THD-10P3, display resolution 640×480, refresh rate 60 Hz)⁽⁸⁾ was employed to present experimental stimuli dichoptically, i.e. one to each eye of the subject. As shown in Fig.1 (a), the images made in the computer were sent into the three-dimensional display device, and through the decoder device, the right eye image and the left eye image were presented on the LCD panel, alternately. The image splitter on the back light is laminated two-layer thin films of aluminum and chromium oxide. By the reflecting action of the image splitter, a subject seated in front of the three-dimensional display device was presented choptically a left view only in left eye and a right view only in right eye, hence perceived a binocular vision. A computer

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Fig. 1. A schematic plan of three-dimensional display device(a), and experimental stimuli consisted of a white stationary fixation dot (b) and a white line target (c) for each eye on a black background

with a software system using Visual C++, was used to control the three-dimensional display to show the experimental stimuli. The distance between the subject and the three-dimensional display device was 70 cm and a chin-rest and head-rest system was used in this experiment for fixing the head of subject against sliding.

The experimental stimuli consisted of a stationary white fixation dot and a white single line for each the left eye view and the right eye view, on a black background. As shown in Fig.1, (b) the fixation dot subtended a visual angle 48 min of arc; (c) the line target subtended a visual angle 48 min of arc in height and 3 min in width.

In this 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 movement in response to a convergence stimulus. This latency period has been found to be 140 ms by Ginsborg⁽⁹⁾, 150-200 ms by Westheimer and Mitchell⁽¹⁰⁾, and 160 ms by Rashbass and Westheimer⁽¹¹⁾. Therefore, the exposure time of the stimuli adopted 140 ms in the present experiment.

2.2 Procedure The present experiment was carried out in the dark room. Firstly, as shown in Fig.2, in step 1, a pair of fixation dots, which were simultaneously projected into the central fovea of left and right eye retinas, were presented for 3 seconds, afterward, the fixation dots were turned off. At the same instant, in step 2, the line stimulus targets separated apart were respectively presented to each eye, and lasted for 140 ms. Then the subject was instructed to respond his or her perception was “single” or “double”, as described in Table 1, which was also used by Diner and Fender⁽¹²⁾. In order to clearly express how to alter the position of the line stimulus target, the polar coordinates were introduced into the present experiment, as shown in Fig.2 (a) and (b). The central point $o(0, 0)$ in the left and right eye views respectively corresponded to the central fovea in the left and right retinas; the x -axis corresponded to the horizontal meridian in the nasal side of retina. The

Table 1. Possible response in experiment

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

Fig. 2. The experiment includes two steps. In step 1, fixation dots appeared in three-dimensional display, and lasted for 3 seconds; In step 2, two line target separated apart are presented dichoptically to each eye for 140 ms, and then subject was asked to respond “single” or “double”; (a) and (b) illustrated the way of changing the line target in left and right eye view according to the polar coordinates

experiment was repeated by altering the position of line stimulus target along the radial coordinate r , only in right retina view (Fig.2 (b)), in a random way between start position and end position. While such alteration, the line stimulus target in the left eye view (Fig.2 (a)) was always fixed in the central fovea of the left retina. The altering interval was 1 pixel in three-dimensional display (about 1.6 min of arc). In all experimental conditions, both line stimulus targets in left and right eye views were set to be always perpendicular to the radial coordinate r .

In the present experiment, sixteen experimental conditions were obtained by varying the polar angle θ from

Fig. 3. The probability of fusion as function of retinal disparity (for subject Y.E) in sixteen different directions

0 degree to 360 degrees by a step of 22.5 degrees. Each experimental condition was repeated 10 times for each subject. Moreover, only one experimental condition was done in one trial for each subject; the interval to next trial was at least one day.

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

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

2.3 Subjects Data were obtained from three male subjects aged between 22 and 24 years. All of them with normal visual acuities and having no oculomotor problem except subject Y.E who had myopia and corrected by contact lenses.

3. Results and Discussion

Although the subject number of three may be few, the results of all subjects were similar. So the results of the probability of fusion only for subject Y.E are shown in Fig.3, which are divided into two parts as nasal side and temporal side, also including the case of 90 degrees and 270 degrees, which belong to neither the nasal nor temporal side. By using a 50 percent fusion criterion as the usual specifying threshold, the threshold disparities of the binocular single vision are obtained and listed in Table 2.

The results shown in Table 2 reveal that the disparity limits in horizontal meridian, the total of nasalward and temporalward disparity limits (0 degree and 180 degrees), are about 32–38.4 min of arc. These values are rather different from some previous results⁽¹⁾⁽²⁾. In fact, not all the previous results are strictly comparable, due to the differences in the experimental techniques, for example, the size of the stimulus target, the exposure time of the target, the criterion of threshold and so on. For example, Palmer⁽¹⁾ 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, the exposure time was 10

Table 2. The limits of binocular fusional area in sixteen directions. (using a 50 percent fusion criterion)

Direction (deg)	Side*	S.N (min)	Y.E (min)	S.T (min)
0	N	25.6	22.4	22.4
22.5	N/D	19.1	15.6	19.1
45	N/D	17.9	15.7	15.7
67.5	N/D	12.1	13.9	12.1
90	D	9.6	12.8	11.2
112.5	T/D	8.7	8.7	8.7
135	T/D	11.2	9	11.2
157.5	T/D	10.4	12.1	8.7
180	T	12.8	12.8	9.6
202.5	T/U	12.1	13.9	10.4
225	T/U	9	11.2	11.2
247.5	T/U	8.7	10.4	8.6
270	U	9.6	11.2	11.2
292.5	N/U	10.3	12.1	13.9
315	N/U	15.7	15.7	17.9
337.5	N/U	17.3	17.3	20.8

*Side of retina: N(Nasal), T(Temporal), U(Up), D(Down).

ms. Mitchell⁽²⁾ also determined this limit about 19 min with a vertical 42 min line, the fusion criterion was 50 percent and the exposure time was 120 ms. We also learn that the vertical disparity limits are about 19.2–24 min of arc, containing upward limits (270 degrees) and downward limits (90 degrees), which are seen evidently smaller than horizontal disparity limits. This point has been reported in many previous experiments⁽³⁾⁽⁶⁾.

In order to clearly express the relation of the limits in different directions, a retinal plan is drawn in Fig.4, inheriting the data in Table 2. The center of the figure is the central fovea of right eye retina. The areas surrounded with different lines are Panum's fusional areas for three subjects. In other words, in the present experiment the line target in left retinal fovea with the line target in right retina, could always fuse into a binocular single vision, if and only if the line target in right retina is fallen within the Panum's fusional area. It is noticed that in this study the direction of fusional area expressed in the Fig.4, such as temporal, nasal, up, down, is based on retina contrary to outside view.

Although Fender and Julesz⁽³⁾ had never measured

Fig. 4. The Panum's fusional areas in right eye retina for three subjects

the limit of temporal side, authors assumed the temporal side was symmetrical with nasal side about vertical meridian, so an ellipse as the form of Panum's fusional was suggested. In the present experiment, as could be seen from Fig.4 that the disparity limits are not symmetrical about vertical meridian, and nasalward limits are larger than temporalward limits. This phenomenon is common to all subjects and could be seen clearly by plotting the ratio of the nasalward limits to temporalward limits, as shown in Fig.5 (a). For all subjects, the disparity limit ratios of the nasal to temporal side are over 1; the minimum value of 1.2 was obtained for subject Y.E in the case of 67.5 degrees (nasal side) to 112.5 degrees (temporal side), and the maximum value of 2.3 was obtained for subject S.T in the case of 0 degree (nasal side) to 180 degrees (temporal side). Richards⁽¹³⁾ also determined the uncrossed and crossed disparity limits, which correspond to the cases of 0 degree (nasalward) and 180 degrees (temporalward) in the present experiment (Fig.4). Richards changed the viewing distance from ∞ to 20 cm, however we used a constant viewing distance of 70 cm. If the viewing distance of 70 cm in the present experiment is applied to the experiment of Richards, we find that the uncrossed (nasalward) disparity limit is larger than the crossed (temporalward) disparity limit for all subjects in his experiment, which is same as our results. These results demonstrate that the fusional area far to a subject from the fixation dot is wider than the area near to the subject from the fixation dot.

As shown in Fig.5 (b), the ratios of downward disparity limit to upward limit are also plotted to show that the curves fluctuated surrounding the value 1, and it seems that the disparity limits are almost symmetrical about horizontal meridian.

Fender and Julesz⁽³⁾ examined the disparity limits at 45 degrees to the horizontal meridian in only nasal

Fig. 5. Ratios of nasalward to temporalward limits (a) and downward to upward limits (b) for three subjects in different directions

side with a moving stimuli target, consisting of nasal-downward and nasal-upward limits, which correspond to the cases of 45 degrees and 315 degrees in the present experiment (Fig.4). Their results revealed these disparity limits were situated between the vertical meridian limit (90 or 270 degrees) and horizontal meridian limit (0 degree). We also obtained similar results in our experiment; the disparity limits decrease monotonically with varying measurement direction from horizontal meridian (0 degree) to vertical meridian (90 or 270 degrees). However, as shown in Fig.4, the situation of temporal side is very different from nasal side. In temporal side, vertical disparity limit, either upward or downward limit, is not minimum, though we forecasted it as the minimum before doing experiment. Actually, there are slight differences of disparity limits in temporal side of retina (from 90 degrees to 270 degrees). The standard deviations of limits in temporal side for three subjects are calculated as 1.5 min of arc for subject S.N, 1.75 min for subject Y.E, and 1.07 min for subject S.T.

In this experiment, we always held the fixation dot in the left retinal fovea, while randomly varying the positions of the line stimulus target in right retina view. The contrary condition never has been done; however we hypothesize the behavior of each of eye is identical.

The different fusion criterion for each subject is certainly one of the important causes affecting the apparent limits of binocular fusional area and individual variation. Furthermore, the resolution of the three-dimensional display device (640×480) could also affect the precision measurements in disparity limit.

4. Conclusions

By measuring the binocular fusional area in sixteen directions, we further confirmed the coincident results with the measurement in eight directions⁽⁷⁾. From the results, we suggest that, in three-dimensional display systems, the horizontal disparity limits about 32–38.4 min and the vertical disparity limits about 19.2–24 min could not be exceeded, otherwise the observer could not obtain a single and comfortable view. In addition, the results reveal that human binocular fusional area in retinal fovea are almost symmetrical about the horizontal meridian. The disparity limits of nasal side and temporal side presented two independent behaviors. In temporal side of retina, the disparity limits have no difference from 90 degrees to 270 degrees. Nevertheless in the nasal side of retina, the disparity limits are found to decrease in a monotonic fashion as measurement direction varying from nasal horizontal meridian (0 degree) to vertical meridian (90 or 270 degrees). Moreover, this study clearly demonstrates that the disparity limits are not symmetrical about vertical meridian, and nasalward limits are larger than temporalward limits.

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