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Double fusion does not occur in Panum's limiting case: evidence from orientation disparity

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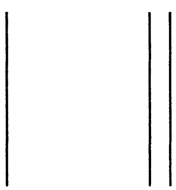
Abstract. When two lines of different orientations are combined in regular stereograms, the orientation of the resulting line is different from those of the monocular lines. In this study we investigate the percept elicited by orientation disparity in Panum's limiting case. A variant of Panum's limiting case was designed to include orientation disparity. The single line in one half-image tilted leftwards. One of the double lines in the other half-image was parallel to the single line, while the other one tilted rightwards with obliquity one third that of the single line. In this stimulus configuration, if the single line in one half-image fuses with both lines in the other half-image at the same time, both of the two lines perceived after fusion should tilt leftwards. If double fusion does not happen, the two lines should tilt leftwards and rightwards respectively. The results of this study are in agreement with the latter prediction, which implies that double fusion does not occur in this variant of Panum's limiting case.

1 Introduction

To reconstruct the three-dimensional world from two-dimensional images on the retinae, features projected from the same object must be recognized and combined. Panum's limiting case, in which a single line is presented to one eye and two lines to the other eye, provides a good stimulus configuration for us to explore the laws exploited by the human brain in stereo vision.

In Panum's limiting case, when the two half-images are combined, two lines can be seen at different depths (see figure 1). Since there is only a single line in one half-image, a question is naturally raised: does the single line fuse with both lines in the other half-image at the same time? To answer this question, different aspects of percepts in Panum's limiting case have been investigated.



left right

Figure 1. Panum's limiting case. When the two half-images are combined, two lines can be perceived at different depths.

Most researchers have concentrated mainly on the differences in depth percept between Panum's limiting case and regular stereograms. Some researchers believed that double fusion happens (Panum 1858; Westheimer 1986; Gillam et al 1995; Kumar 1996). The depths of the two lines perceived derive directly from their disparities. Others argued that double fusion does not happen and the depth percepts of the two lines originate from nonstereoscopic factors such as occlusion (Nakayama and Shimojo 1990; Ono et al 1992; Chang et al 1993; compare Blackburn et al 1995), camouflage (Howard and Ohmi 1992), or misconvergence (Howard and Rogers 1995; Shimono et al 1999).

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Nakamizo et al (1994) studied visual directions of the lines in Panum's limiting case. Because visual directions of monocular features and those of binocular features obey different laws (Nakamizo et al 1994; Ono and Mapp 1995), it can be determined whether double fusion happens in Panum's limiting case. They found that "visual direction of the far stimulus was veridical only with convergence at the far plane" (page 1037). This result supports the hypothesis that double fusion does not occur.

McKee et al (1995) investigated the binocular masking effect in Panum's limiting case. In their stimulus, "a single high-spatial-frequency target in the left eye was paired stereoscopically with two identical targets presented near retinal correspondence (±3.5 min of disparity), in the right eye". They measured contrast-increment thresholds for each target and found that the target in the left eye masked both targets in the right eye. They concluded that "the target in the left eye had been matched to both targets in the right eye" (page 49).

In this study, a demonstration and an experiment were designed to investigate orientation disparity in Panum's limiting case. Because the orientation of a monocular line will change when it is combined with another line with a different orientation, we can determine whether the two lines in Panum's limiting case are monocular or binocular.

2 Demonstration

When two lines of different orientations are presented to the left and right eyes, the perceived orientation of the line is different from those of the monocular ones. As illustrated in figure 2, after fusion, the perceived orientation of the line (F) lies between that of the line presented to the left eye (L) and that of the line presented to the right eye (R). (Actually, the perceived line tilts in depth. In figure 2, F depicts its projection onto the frontoparallel plane.)

In the stimulus for the demonstration (see figure 3), two left-tilting lines were placed such that they had zero disparity. Another right-tilting line was added to the right side of the lines in the right-eye image. The angle between the right-tilting line and vertical was one third that of the left-tilting lines. If double fusion happens,

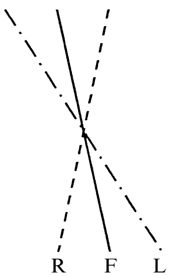

Figure 2. Orientation disparity in a regular stereogram. When two lines of different orientations (L and R) are combined, the orientation of the resulting line (F) is different from those of the monocular ones.

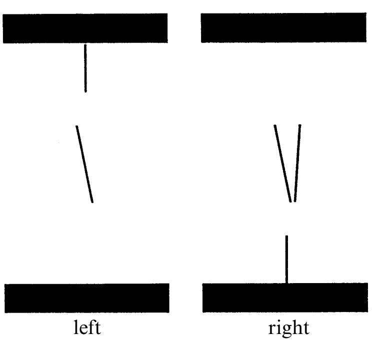

Figure 3. Stimulus for the demonstration. See text for details.

the right-tilting line in the right-eye image should fuse with the left-tilting line in the left-eye image. The resulting orientation should be F (see figure 2). If double fusion does not happen, only the two left-tilting lines should fuse because they have zero disparity and are similar in orientation. The right-tilting line should remain monocular and its orientation should be R. To make the distinction between Panum's limiting case and regular stereograms more obvious, the left-tilting line in the right-eye image was removed after subjects fused the left and right images. This makes the right-tilting line in the right-eye image fuse with the left-tilting line in the left-eye image. If the right-tilting line had been monocular before the removal of the left-tilting line in the right eye, it should jump leftward after the left-tilting line in the right-eye image disappeared. If the double fusion hypothesis is correct, no changes should be visible.

2.1 *Method*

2.1.1 *Stimulus and apparatus.* The stimuli were generated by a Windows NT graphics workstation and presented on a Mag XJ700T monitor with a resolution of 1024 pixels $\times$ 768 pixels and a refresh rate of 75 Hz. A stereoscope was used to help subjects fuse the stereogram and to ensure a viewing distance of 60 cm. The left or right image subtended 3.3 deg $\times$ 5.9 deg. All lines were 91.7 min of arc in height. The left-tilting lines and the right-tilting line formed acute angles of 6.9° and 2.3° with the vertical, respectively. The horizontal separation between the middle points of the two lines in the right eye was 11.0 min of arc. Nonius lines (57.3 min of arc in length) were added to monitor eye position.

2.1.2 *Procedure.* After fusion was obtained and the nonius lines appeared aligned, a key was hit to make the left-tilting line in the right eye disappear. Subjects were asked to observe whether there were any changes in the obliquity of the line on the right before and after the left-tilting line in the right eye disappeared. They were also instructed to give a report only when the nonius lines appeared aligned throughout the demonstration.

2.1.3 *Subjects.* Three subjects (two male and one female) with normal binocular vision participated in the demonstration. Two (WZ, NR) were the authors and the other one (LY) was naïve concerning the purpose of the experiment.

2.2 *Results*

All subjects reported having noticed a leftward jump of the right-hand-side line. Before the disappearance of the left-tilting line in the right eye, the right-hand-side line was seen to be tilted rightward. After the left-tilting line in the right eye disappeared, the line was seen to be tilted leftward. This result implies that the right-hand-side line derives its orientation in the frontoparallel plane from one eye only and that double fusion does not happen in this variant of Panum's limiting case.

3 Experiment

In the demonstration, we monitored subjects' vergence by using nonius lines and asking subjects to keep them aligned. But there still are possibilities that the vergence might have changed without being noticed. To rule out this possibility, we conducted the following experiment, in which stereograms were shown for a short period of time (160 ms).

3.1 *Method*

3.1.1 *Stimuli and apparatus.* The viewing apparatus was as described for the demonstration except that the viewing distance was 120 cm. Three types of sterograms were used. Figure 4a shows the cue before a trial starts. The width and height of the nonius cross were both 27.5 min of arc. When fused, the center of the cross was on the mid-sagittal plane. Figure 4b shows the stimulus for Panum's limiting case. The heights of the lines were 45.8 min of arc. The single line in one eye and the line of the same obliquity in the

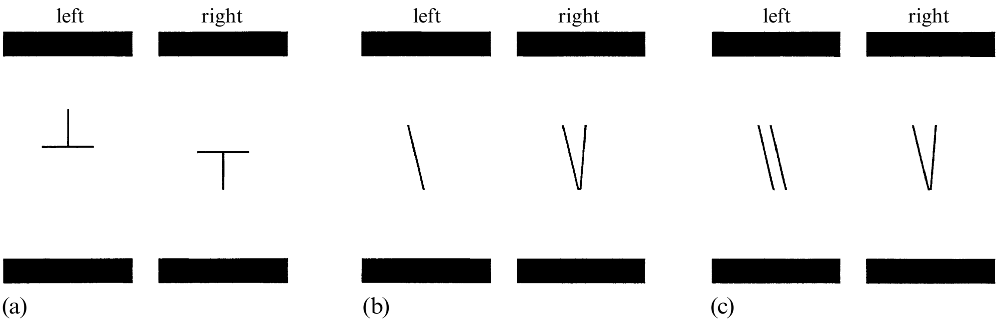

Figure 4. The cue stereogram (a), Panum's limiting case (b), and the regular stereogram (c) used in the experiment. See text for details.

other eye had zero disparity. We called them zero-disparity lines. We called the right-tilting line the Panum line. Figure 4c shows a regular stereogram. A new line parallel to the single line in figure 4b was added to the image that contained the single line. We called this newly added line the regular line. The middle point of the Panum line and the regular line fell on corresponding points on the retinae. The obliquity of the zero-disparity lines and the Panum line was the same as in the demonstration.

3.1.2 *Procedure.* Each trial began with the presentation of the stereogram illustrated in figure 4a. After fusion was obtained and the nonius lines appeared aligned, either a regular stereogram or Panum's limiting case was shown for 160 ms. Subjects were asked to report the directions towards which the perceived two lines tilted. Four factors—the eye that viewed the Panum line (left eye or right eye), the direction towards which the Panum line tilted (tilt left or tilt right), the type of stereogram (regular or Panum), and the separation of the middle point of the double lines (11.0, 14.7, 18.3, 22.0, 25.7 min of arc)—were factorially combined to give a total of forty conditions. Each condition was tested ten times in a randomized order for each subject.

3.1.3 *Subjects.* Subjects were the same as described in the demonstration.

3.2 *Results and discussion*

In regular stereograms, the perceived lines should tilt towards the same direction, although their obliquities will be different. In Panum's limiting cases, if double fusion happens, the two perceived lines should also tilt towards the same direction. Again, their obliquities should be different. If double fusion does not happen, the two zero-disparity lines should fuse and the Panum line should remain monocular. So, the two perceived lines should tilt towards different directions in this case.

As the results shown in figure 5 indicate, subjects' responses to regular stereograms are different from those in Panum's limiting cases. The number of the trials on which the perceived orientations agree with those predicted by binocular fusion in regular stereograms is much higher for regular stereograms than for Panum's limiting cases in spite of similar stimulus configurations. This result is different from those obtained by Gillam et al (1995). They found that, although in 'patent disparity' (up to approximately 16 min of arc) the depth percepts can be obtained with an accuracy indistinguishable from that for regular stereograms, the vivid depth percepts are increasingly hampered as the disparity becomes larger. Our results show that the number of trials on which the perceived orientations agree with those predicted by binocular fusion when the disparity lies in 'patent disparity' (see the data for the between-line separation of 11 min of arc in figure 5) is roughly the same as for when the disparity is larger. This suggests that in Panum's limiting cases (whether the disparity falls in 'patent disparity' or not) the double lines do not fuse with the single line at the same time.

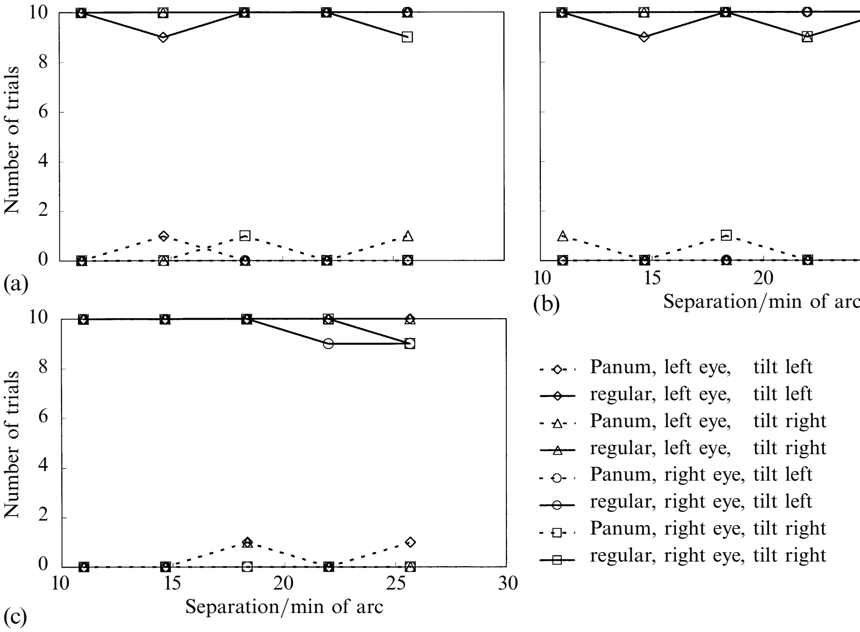

Figure 5. Results of the experiment for three subjects—(a) LY, (b) NR, (c) WZ. The number of trials on which the orientations of the two perceived lines agreed with those predicted by binocular fusion are drawn, for each condition, against different separations between the Panum line and the zero-disparity line in the half-image containing the Panum line.

Westheimer (1986) also studied the depth percepts in Panum's limiting cases when the line separations were systematically changed. He found that when the line separations were small (less than 10 min of arc), subjects could correctly identify the depth relationship of the two perceived lines. When the line separations increased, the ratio of the correct responses declined steeply. Therefore, one may argue that our results only confirm that double fusion has a stringent disparity limit, not that it does not occur when the line separations are small (less than 10 min of arc). To test this possibility, we conducted a further experiment in which the horizontal separations between the middle points of the Panum line and the zero-disparity line in the half-image containing the Panum line were reduced to 4.8 min of arc (since the lines were tilted, the maximum separation was 5.8 min of arc and the minimum separation was 3.8 min of arc). Since the line separations are well below the disparity limit obtained from Westheimer's experiment, if double fusion happens, we would observe it. (To make sure that the apparent tilt of the fused line falls halfway between the half-images as predicted from the geometry, we conducted a pilot experiment in which the stimuli were the same as the Panum stimuli in the further experiment except that one of the zero-disparity lines was removed, and so stimuli presented to each eye contained only one line. The results showed that the two lines fuse and that the direction of the apparent tilt reported by the observers was the same as in the prediction.)

The stimuli for the further experiment were generated by a Windows NT graphics workstation and presented on an EIZO T57S monitor with a resolution of 1920 pixels $\times$ 1200 pixels and a refresh rate of 70 Hz. The viewing distance was 120 cm. The left and right images both subtended 24.0 min of arc $\times$ 36.0 min of arc. All lines were 24.0 min of arc in height. The left-tilting lines and the right-tilting line formed acute angles of 6.9° and 2.3° with vertical direction respectively. Nonius lines were 14.4 min of arc in height. The presentation duration was 170 ms. We calculated the proportions of responses in which the orientations of the perceived lines agreed with those predicted by binocular fusion in Panum stereograms. The results showed that for all subjects the ratios were very low (WZ—1.3%; NR—3.8%; ZL—8.8%). This confirmed our previous suggestion that double fusion does not occur.

Subjects noticed in the variant of Panum's limiting case used in the experiment that the Panum line appears slanted in depth (in figure 4b it slants into the paper with the lower end nearer than the upper end) and its midpoint is more distant than the zero-disparity line. As can be seen in figure 4b, the zero-disparity lines tend to fuse and give rise to a percept of a left-tilting line lying in the zero-disparity plane. The separation between the left-tilting line and the right-tilting line increases gradually when viewed from bottom to top. It is possible that this geometrical information is actually used by the visual system to confer depth to the Panum line. We suggest that while our experiment shows that there is no effective binocular interaction between the Panum line and the zero-disparity line for the processing of orientation disparity, there may be such interaction for depth recovery.

Since the receptive fields of disparity sensitive neurons tend to be oriented (Ohzawa et al 1996; Ohzawa et al 1997), it is possible that orientation-disparity processing and disparity detection are coupled tightly in the visual system. The fact that no effective binocular interaction occurred between the Panum line and the zero-disparity line for the processing of orientation disparity suggests that double matching may not happen either.

Some researchers have argued that fusion and matching may involve the same neural mechanism (Anderson and Nakayama 1994). If this is true then, from our results of orientation-disparity processing in Panum's limiting case, we can infer that not only double fusion but also double matching does not occur.

If double matching is not likely to be the reason for the depth percepts in Panum's limiting case, what is? Since the plane passing through the left eye and the left-tilting line and the plane passing through the right eye and the right-tilting line (see figure 4b) will never be parallel, they always intersect each other at a line tilting in depth which is occluded by the nearer left-tilting line in the view through the left eye. Thus, the displays used in the demonstration and the experiment were always consistent with a farther line (the right-tilting line in figure 4b) being occluded by a nearer line (the left-tilting line in figure 4b) in the view through one eye (the left eye in the case of figure 4b), although the slope of the Panum line depends on the viewing distance and the angles and separations of the lines in the stimuli. It might be just the occlusion relationship that causes the depth percepts in Panum's limiting case (Nakayama and Shimojo 1990; Ono et al 1992; Chang et al 1993).

As Shimono et al (1999) reported, occlusion provides information about depth order but no information about depth magnitude. This limitation may be the result of the design of their stereograms. Since they used thick bars in their stereograms and the thickness of the double bars was different, the occlusion geometry predicted that the occluded bar could lie within a depth range. In our experiment, the three lines were thin and identical in thickness. The occlusion geometry should give definite depth information in our case.

In the variant of Panum's limiting case used in this study, the single line fell on corresponding points with one of the double lines and lay parallel to it. These two factors make it easier for the single line to fuse with one of the double lines than with the other one. Our results show that double fusion does not happen in this condition. It does not rule out the possibility that double fusion may happen when the two fusions are equivalent (McKee et al 1995).

That double fusion does not occur at the same time in our version of Panum's limiting case conforms to the idea of a disparity-gradient constraint (Burt and Julesz 1980; Pollard et al 1985). This constraint, which is widely used in computational modeling of stereo vision, dictates that a feature in one eye cannot be fused with more than one feature in the other eye.

Further studies have to be done to account for the fact that depth is perceived with a precision and accuracy indistinguishable from regular stereopsis in Panum's limiting case (Gillam et al 1995) and that the target in the left eye masked both targets in the right eye (McKee et al 1995).

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