Research on the Double Fusion Depth Mechanism in Panum' s Limiting Case

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Abstract

Panum' s limiting case represents the simplest phenomenon within monocular regions and serves as a crucial entry point for investigating the mechanisms underlying stereoscopic vision formation in monocular occlusion zones. This study presents an in-depth investigation into the existing controversy regarding the origin of depth in Panum' s limiting case. The experiment utilized a fixed fixation point position and rapid stimulus presentation to examine whether observers could accurately perceive the depth of both fixated and non-fixated features, and to determine whether the perceived depth arose from depth contrast. The results demonstrate that, under both Panum stimulus conditions and control stimulus conditions, observers were able to correctly perceive the depth of fixated and non-fixated features, and that the depth of the two features perceived following binocular fusion did not originate from depth contrast. This indicates that the depth perception mechanism in Panum' s limiting case is more likely attributable to double fusion.

Full Text

The Study of Double Fusion Depth Mechanism in Panum' s Limiting Case

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Abstract

Panum's limiting case represents one of the simplest configurations in monocular regions and serves as a breakthrough for investigating the stereopsis mechanism formed by monocular occlusion regions. This study addresses the ongoing controversy regarding the origin of depth in Panum's limiting case through in-depth research. Using a fixed fixation point and rapid stimulus presentation, the experiment examined whether subjects could correctly perceive the depth of both fixation and non-fixation features, and whether perceived depth originated from depth contrast. Results demonstrated that subjects could accurately perceive the depth of both fixation and non-fixation features under both Panum and control stimulus conditions. Moreover, the depth of the two features perceived after binocular fusion did not arise from depth contrast, suggesting that the depth perception mechanism in Panum' s limiting case is more likely double fusion.

Keywords: stereopsis, monocular regions, Panum' s limiting case, depth contrast, double fusion

Introduction

Stereopsis is a cognitive process that achieves spatial information perception, such as object distance and depth, through binocular fusion. Binocular disparity serves as a crucial depth cue in stereopsis, sometimes referred to as stereoscopic disparity. In typical real-world scenes, objects can find their corresponding matches in both eyes, allowing depth estimation based on binocular disparity. However, monocular regions present an exception. In natural visual scenes involving opaque objects at different depths, an observer' s line of sight may be obstructed by these objects, causing certain areas to be visible to only one eye while remaining invisible to the other. The unique characteristic of monocular regions is that features presented to one eye lack corresponding matches in the other eye, making depth estimation based on binocular disparity impossible (Cook & Gillam, 2004), which poses significant challenges to stereopsis research.

Panum' s limiting case represents the simplest configuration within monocular regions. It occurs when two opaque objects at different depths align along the same line of sight to one eye, causing that eye to be completely unable to see the more distant object. In this situation, only one feature is presented to one eye while two features are presented to the other eye. After binocular fusion, the observer can perceive the depth of both objects (Gillam, Blackburn, & Nakayama, 1999; Panum, 1858).

Two opposing theoretical perspectives have emerged regarding its depth processing mechanism: unique fusion and double fusion. Unique fusion posits that the paired features presented to one eye can only match with the single feature presented to the other eye. Consequently, among the two perceived features, one derives its depth from interocular feature matching while the other obtains depth from alternative cues such as occlusion, camouflage, oculomotor error, or suppression mechanisms (Bingushi & Yukumatsu, 2005; Frisby, 2001; Howard & Rogers, 2012; Wang, Wu, Ni, & Wang, 2001). Double fusion, conversely, proposes that both features in the paired presentation match with the single feature from the other eye, resulting in both features exhibiting distinct depth variations in three-dimensional space after binocular fusion (Gillam, 1995). This perspective maintains that the depth of both perceived features originates from conventional binocular matching.

Recent studies employing different stimulus configurations have yielded contradictory conclusions regarding depth processing mechanisms. Specifically, under small disparity conditions, both Panum line configurations and Gillam curve configurations support double fusion, whereas Frisby wave line configurations and Wang oblique line configurations support unique fusion. These three distinct stimulus configurations have created a completely polarized debate between double fusion and unique fusion (Frisby, 2001; Gillam, 1995; Wang et al., 2001). Subsequent researchers developed fold-line stimuli with slant effects to address limitations in previous configurations. In fold-line configurations, a single broken line is presented to one eye while two different broken lines are presented to the other eye. If observers perceive both broken lines as having slant effects, the result supports double fusion; if only one broken line exhibits slant effects, the result supports unique fusion. Additional research suggests that during stereopsis formation in monocular regions, double or even multiple fusion represents the common state, while unique fusion constitutes merely a special case (Li, Xie, Li, & Li, 2011).

However, previous studies have raised 质疑, suggesting that in Panum' s limiting case, the perceived depth of two features after binocular fusion may not result from double fusion but rather from depth contrast. Depth contrast refers to a phenomenon where a feature adjacent to another feature with binocular disparity is perceived as having depth, even though it actually lies on the zero plane. This occurs because observers make depth comparisons between the two features, enabling judgments about the adjacent feature' s depth (Howard & Rogers, 2012). Due to depth contrast effects, some researchers have proposed that in Panum' s limiting case, the perceived depth order of two features after binocular fusion arises from one feature' s depth generated through binocular matching and the other feature' s depth produced by depth contrast rather than genuine binocular matching (EE & Erkelens, 1996; O' Shea, Blackburn, & Ono, 1994). Consequently, these results do not support double fusion.

This study employs rapid stimulus presentation using fold-line Panum stimulus configurations to investigate the depth origin in monocular regions. Experiment 1A first examines subjects'depth perception of fixation features and subsequently investigates perception of non-fixation features to assess whether double fusion occurs in Panum' s limiting case. Ideally, one experiment should simultaneously examine depth perception of both features after binocular fusion. However, due to the brief stimulus presentation duration in this study, requiring subjects to report the depth of both features after stimulus offset would impose excessive cognitive load and likely introduce errors. As Nakayama and Shimojo (1990) noted, in their experiments, disparity probes presented simultaneously with stimuli affected the perceived depth of monocular objects, while sequential presentation of stimuli and probes increased memory load and response noise (Nakayama & Shimojo, 1990). Therefore, this study implements Experiment 1A and Experiment 1B, controlling subjects' fixation position and stimulus presentation duration to separately examine depth perception of fixation and non-fixation features, thereby determining whether the depth mechanism in Panum' s limiting case involves double fusion or unique fusion.

Furthermore, previous research has suggested that due to depth contrast effects, the perceived depth order of two features in Panum' s limiting case originates from binocular feature matching for one feature and depth contrast for the other, rather than genuine binocular matching, thus not supporting double fusion. Building upon Experiment 1, this study designs Experiment 2 to investigate whether depth perception results in Panum' s limiting case arise from double fusion, thereby addressing previous 质疑 regarding depth contrast phenomena. Both experiments employ fixation point presentation to strictly control vergence eye movements and maintain consistent fusion patterns (Wang et al., 2001), allowing subjects' natural eye movement participation in visual perception formation. However, it remains possible that such vergence changes occur without conscious awareness. To exclude this possibility, the following experiments adopt rapid stimulus presentation (200 ms) to examine whether subjects can still perceive double fusion and to compare results with previous studies.

Experiment 1A: Depth Perception of Fixation Features

Previous studies have demonstrated that under small disparity conditions, subjects perceive double fusion in fold-line Panum stimulus configurations at frequencies exceeding 90% (Li et al., 2011; H. Li et al., 2012). However, these studies did not consider whether fixation position and stimulus presentation duration during the experimental process might influence depth perception outcomes. This limitation prevents determination of whether perceived double fusion results from simultaneous matching, as stable rapid alternating matching can produce identical perceptual results to double fusion. Therefore, through Experiments 1A and 1B, we controlled subjects' fixation position and stimulus presentation duration to separately examine depth perception of fixation and non-fixation features. Fixation and non-fixation features are defined relative to whether the subject' s fixation point falls on a particular feature within the stimulus configuration. If the fixation point lies on a specific feature, that feature constitutes the fixation feature, while the other feature serves as the non-fixation feature.

2.1.1 Subjects

Eleven undergraduate and graduate students participated in this experiment (5 males), aged 19–28 years (mean age = 23.18 ± 2.69 years). All subjects had monocular visual acuity or corrected visual acuity of 1.0 or better with no psychiatric or organic disorders. Stereoacuity was assessed using Randot™

stereotest, requiring results above 20 arc seconds for study participation. All observers signed informed consent forms before the experiment. All experimental procedures complied with local ethics committee approval and followed the Declaration of Helsinki.

2.1.2 Apparatus

This experiment employed a self-built visual data acquisition system. Stimiments requiring computer presentation were programmed using MATLAB 7.12.0 software and the PsychToolbox (Brainard, 1997; Pelli, 1997). Stimuli were presented on two DELL color monitors with resolution set to 1920$×$1200 and refresh rate of 75Hz. A Wheatstone stereoscope achieved dichoptic presentation. The entire experiment was conducted in a dark room with a viewing distance of 74 cm. Under these resolution and viewing distance conditions, each pixel on the monitor screen subtended 1.26 arcmin. To maintain constant head-to-monitor distance, subjects placed their chins on a chinrest while viewing stimuli and responded using a keyboard.

2.1.3 Stimuli

As shown in Figure 1 [Figure 1: see original paper], this experiment employed three stimulus types: Panum stimuli and Type I and Type II control stimuli. Panum stimuli follow the same construction principle as commonly used stimuli in previous Panum' s limiting case research, presenting a single feature to one eye and two features to the other eye. Type I and Type II control stimuli differ from Panum stimuli in that they represent conventional stereoscopic stimuli, with equal numbers of features presented to both eyes, allowing each feature to find its corresponding retinal image. Consequently, their depth can be quantitatively estimated based on binocular disparity, which we term "expected depth." Expected depth results can be compared with subjects' actual depth perception to assess potential misreporting in control stimuli and to infer the matching mechanism of features in Panum stimuli by comparing depth perception results between Panum and control stimuli.

Figure 1 illustrates the three stimulus types used in Experiment 1A. Figure 1A shows Panum stimuli, where the fixation feature refers to the feature whose broken line vertex aligns with the fixation point location before stimulus presentation. Figure 1B shows Type I control stimuli, where the small broken line serves as the fixation feature; subjects must maintain fixation on the small broken line before presentation and report its depth afterward. Figure 1C shows Type II control stimuli, where the large broken line is the fixation feature; subjects fixate on the large broken line before presentation and report its depth.

All three configurations contain both large and small broken lines. For convenience, we refer to the line farther from the straight line as the "large broken line" and the line closer to the straight line as the "small broken line." In Panum stimuli, the single feature presented to one eye is called the "single feature," while the two lines presented to the other eye are called the "paired features." In Panum stimuli, the vertex angle between the single feature' s broken line and the straight line is 1.5 arcmin, while in paired features, the vertex angles for large and small broken lines are 1.8 arcmin and 1.2 arcmin, respectively. Therefore, during binocular fusion, regardless of which broken line the single feature matches with in the paired features, the binocular disparity is $±$0.3 arcmin.

For Type I control stimuli, the vertex angle between the large broken line and straight line is 1.8 arcmin in both eyes, while the vertex angle for the small broken line is 1.2 arcmin in one eye and 1.5 arcmin in the other. Consequently, after binocular fusion, the large broken line has zero disparity while the small broken line has $±$0.3 arcmin disparity. For Type II control stimuli, the large broken line' s vertex angle is 1.5 arcmin in one eye and 1.8 arcmin in the other, while the small broken line' s vertex angle is 1.2 arcmin in both eyes. Thus, after binocular fusion, the large broken line has $±$0.3 arcmin disparity while the small broken line has zero disparity.

This study adopts the conventional representation method in binocular vision research for stimulus presentation in schematic diagrams (Tsirlin, Wilcox, & Allison, 2011; Wardle & Gillam, 2013). As shown in Figure 1, the three stimulus columns represent presentation to the left or right eye, with identical stimuli in the first and third columns. For Panum stimuli, in one trial, the single feature from the first column is presented to the left eye while the paired features from the second column are presented to the right eye; in another trial, the paired features are presented to the left eye and the single feature to the right eye, enabling stimulus alternation between eyes.

In all three stimulus types, both single and paired features have a straight line on either their left or right side to facilitate more accurate depth judgments. This straight line has zero binocular disparity and lies exactly on the zero plane after fusion, serving as a reference surface for depth judgments. All stimuli consist of straight and broken lines with thickness of 2.5 arcmin. During the experiment, a red fixation dot with diameter of 12.6 arcmin guided subjects to focus on specified locations. The stimulus background was gray with luminance of 46 cd/m^2.

2.1.4 Procedure

The experimental procedure is illustrated in Figure 2 [Figure 2: see original paper]. Initially, a red fixation dot appeared at the center of the straight line. After subjects pressed a key when ready, the fixation dot disappeared for 300 ms. Subsequently, the fixation dot reappeared at either the small or large broken line location for 750 ms. Stimuli then presented for 200 ms, comprising any of the Panum, Type I, or Type II control stimuli shown in Figure 1. The broken line could appear on either the left or right side of the straight line. During the response phase, subjects reported whether the plane containing the broken line at the fixation point location slanted forward or backward relative to the zero plane defined by the straight line. After each trial, subjects redirected attention to the red fixation dot at the straight line' s center in preparation for the next trial.

Throughout the experiment, subjects maintained gaze on the red fixation dot location. Critically, between fixation dot disappearance and reappearance, subjects had to maintain gaze at the previously cued location. For example, if the fixation dot appeared at the large broken line location before stimulus presentation, subjects had to maintain gaze at that location during stimulus presentation even after the fixation dot disappeared. While most subjects found it relatively easy to maintain gaze at the previously cued location during stimulus presentation, they often could not determine whether the large or small broken line occupied the fixation point location after stimulus offset, making it difficult to know which line' s depth to judge. To help subjects identify the fixation feature more easily, we used a hollow red dot when the fixation point was at the small broken line vertex and a solid red dot when at the large broken line vertex.

Figure 2 [Figure 2: see original paper] shows the procedure for Experiment 1A. For the three stimulus types in Figure 1, the fixation point could appear at either the small or large broken line vertex, with broken line orientation on either the left or right side of the straight line, and stimuli presented to left and right eyes alternated across trials. Therefore, Panum stimuli comprised 8 conditions, while Type I and Type II control stimuli each comprised 8 conditions, totaling 16 control stimulus conditions. Before the formal experiment, subjects participated in relevant stereopsis tests and a practice experiment identical to the formal procedure. The formal experiment included 2 blocks with rest periods between them. In each block, each of the 8 Panum stimulus conditions was presented randomly 10 times, and each of the 16 control stimulus conditions was presented randomly 5 times, resulting in 160 trials per block and 320 trials total.

2.2 Results

Since differences in stimuli presented to left versus right eyes were not of interest, results from these conditions were combined. Additionally, Type I and Type II control stimuli served only to prevent subject misreporting and to examine depth perception of large and small broken lines in conventional stimuli for comparison with Panum stimuli; differences between Type I and Type II control stimuli were not meaningful for this study. Therefore, Type I and Type II results were combined as control stimulus results in data analysis. The final statistical analysis examined results from Panum and control stimuli across four experimental conditions: fixation feature as small or large broken line, and broken line orientation on the left or right side of the straight line.

For each condition, we calculated the probability that subjects' depth perception of the fixation feature matched the expected depth, hereafter termed “consistent probability.” Expected depth for Panum stimuli refers to the depth estimated from binocular disparity when the single feature in one eye matches the fixation feature in the other eye. For control stimuli, expected depth refers to the depth estimated from binocular disparity when the fixation broken line matches its corresponding broken line in the other eye.

Statistical analysis was performed using SPSS 17.0. A three-way repeated measures ANOVA was conducted on consistent probability with factors of fixation feature (small broken line, large broken line), stimulus type (Panum stimulus, control stimulus), and broken line orientation (left side of straight line, right side of straight line). P-values were corrected using the Greenhouse-Geisser method, and pairwise comparisons were Bonferroni-corrected.

ANOVA results revealed a significant main effect of stimulus type, $F(1, 10) = 13.81$, $p < 0.01$, $\mathrm{p}^2 = 0.58$. Post-hoc comparisons indicated that consistent probability was significantly lower for Panum stimuli than for control stimuli. Additionally, the interaction between fixation feature and stimulus type was significant, $F(1, 10) = 9.54$, $p < 0.01$, $\mathrm{p}^2 = 0.49$. Simple effects analysis showed that when the fixation feature was the small broken line, consistent probability was significantly lower for Panum stimuli than control stimuli ($p < 0.01$), but no significant difference existed when the fixation feature was the large broken line ($p > 0.05$). No other main effects or interactions were significant ($p > 0.05$).

Figure 3 [Figure 3: see original paper] displays the results for fixation features. The vertical axis represents the probability of matching expected results, while the horizontal axis shows results across four experimental conditions for Panum and control stimuli. Dark and light gray bars represent results when fixation features were small and large broken lines, respectively.

Figure 3 reveals that: (1) across all four Panum stimulus conditions, consistent probability between perceived depth and expected depth approached 90%; and (2) across all four control stimulus conditions, consistent probability exceeded 90%.

In addition to ANOVA, paired samples *t*-tests compared consistent probabilities across conditions against chance probability. Results showed that consistent probabilities in all conditions were significantly higher than chance. Chance probability refers to the percentage of each perceptual outcome among all possible outcomes. In Experiment 1A, subjects had only two depth judgment options (forward or backward slant), yielding a chance probability of 50%.

Experiment 1B: Depth Perception of Non-Fixation Features

In Experiment 1A, based on previous research (H. Li et al., 2012), we had reason to believe subjects could judge fixation feature depth, thus providing only two response options. However, in Experiment 1B, subjects had to maintain fixation on the fixation feature during stimulus presentation while reporting the depth of the non-fixation feature after stimulus offset. This could lead to matching between the single feature in one eye and the fixation feature in the other eye, without matching to the non-fixation feature, or cause subjects to perceive the non-fixation feature as lying on the zero plane due to lack of conscious attention. Therefore, to ensure accurate reporting, Experiment 1B provided three response options: the non-fixation feature' s plane could slant forward, backward, or lie on the zero plane.

3.1 Method

Subjects and apparatus were identical to Experiment 1A. Stimuli were similar to those in Experiment 1A, including Panum stimuli and Type I and Type II control stimuli. The key difference was that in Experiment 1A, the fixation feature had $±$0.3 arcmin disparity while the non-fixation feature had zero disparity, whereas in Experiment 1B, the non-fixation feature had $±$0.3 arcmin disparity while the fixation feature had zero disparity. Additionally, the procedure differed: subjects maintained gaze at the previously cued fixation location during stimulus presentation but reported the depth of the non-fixation feature after stimulus offset.

Using Type I control stimuli from Experiment 1A as an example (Figure 4 [Figure 4: see original paper]), we can illustrate differences in fixation position between experiments. In Experiment 1A, which examined fixation feature depth perception, the small broken line served as the fixation feature with $±$0.3 arcmin disparity, while the large broken line was the non-fixation feature with zero disparity. Subjects maintained fixation on the small broken line before and during stimulus presentation, then reported its depth. In Experiment 1B, which examined non-fixation feature depth, the small broken line became the non-fixation feature with $±$0.3 arcmin disparity, while the large broken line was the fixation feature with zero disparity. Subjects fixated on the large broken line before and during presentation, but reported the small broken line' s depth afterward. Thus, despite identical stimuli and tasks, fixation positions differed between experiments due to different experimental purposes.

3.2 Results

For the same reasons as in Experiment 1A, results from stimuli presented to left versus right eyes (including Panum, Type I, and Type II control stimuli) were combined across trials. Additionally, based on Experiment 1A results showing no significant main effect of broken line orientation, indicating no difference in consistent probability between left and right side presentations, results from these conditions were also combined. After these data processing steps, we calculated for each subject: (1) the consistent probability between perceived depth and expected depth for non-fixation features in Panum and control stimulus conditions when the non-fixation feature was the small or large broken line; and (2) the probability of perceiving depth at zero disparity (hereafter "zero-disparity probability").

Statistical analysis was performed using SPSS 17.0. Two-way repeated measures ANOVAs were conducted separately on consistent probability and zero-disparity probability with factors of non-fixation feature (large broken line, small broken line) and stimulus type (Panum stimulus, control stimulus). P-values were Greenhouse-Geisser corrected, and pairwise comparisons were Bonferroni-corrected.

For consistent probability (Figure 5A [Figure 5: see original paper]), ANOVA results showed: (1) a significant main effect of non-fixation feature, $F(1, 10) = 5.411$, $p < 0.05$, $\text{p}^2 = 0.351$, indicating significant differences in consistent probability between large and small broken lines. Specifically, consistent probability was significantly lower when the non-fixation feature was the small broken line compared to the large broken line; (2) a significant main effect of stimulus type, $F(1, 10) = 6.413$, $p < 0.05$, $\text{p}^2 = 0.391$, indicating stimulus type significantly affected consistent probability, with post-hoc tests showing significantly lower consistent probability for Panum stimuli than control stimuli; and (3) no significant interaction between non-fixation feature and stimulus type ($p > 0.05$).

For zero-disparity probability (Figure 5B), ANOVA results showed: (1) a significant main effect of non-fixation feature, $F(1, 10) = 6.01$, $p < 0.05$, $\text{p}^2 = 0.38$, indicating significant differences in zero-disparity probability between large and small broken lines. Specifically, zero-disparity probability was significantly higher when the non-fixation feature was the small broken line; (2) no significant main effect of stimulus type ($p > 0.05$); and (3) a significant interaction between non-fixation feature and stimulus type, $F(1, 10) = 7.26$, $p < 0.05$, $\text{p}^2 = 0.42$. Simple effects analysis revealed that in Panum stimulus conditions, zero-disparity probability was significantly higher for small broken lines than large broken lines ($p < 0.01$), while in control stimulus conditions, this difference was also significant ($p < 0.05$).

Paired samples t-tests compared consistent probabilities and zero-disparity probabilities against chance probability. Results showed: (1) consistent probabilities in all conditions were significantly higher than chance ($p < 0.05$). With three response options in Experiment 1B, chance probability was 33.3% for each outcome; and (2) for both Panum and control stimuli, zero-disparity probability differed significantly from chance when the non-fixation feature was the small broken line ($p < 0.05$), but was significantly lower than chance when the non-fixation feature was the large broken line ($p < 0.01$).

Experiment 2: Relationship Between Subjects' Perceptual Results and Depth Contrast

The results from Experiments 1A and 1B indicate that for fold-line Panum stimulus configurations, subjects can perceive depth in the planes containing both features after binocular fusion, supporting double fusion. However, most researchers opposing double fusion argue that fixation feature depth originates from feature matching while non-fixation feature depth derives from other cues.

Therefore, 质疑 regarding depth contrast in Panum' s limiting case primarily target non-fixation features.

To address this, Experiment 2 was designed to verify whether depth perception results in Panum' s limiting case originate from depth contrast. We hypothesized that if one feature' s depth in Panum stimuli indeed results from depth contrast, that feature' s depth should be influenced by the other feature. When the feature generating depth through binocular disparity disappears, subjects should perceive a change in the other feature' s depth. The design logic was: if non-fixation feature depth perception truly results from depth contrast, subjects should perceive a change in non-fixation feature depth when the fixation feature disappears; conversely, if non-fixation feature depth perception results from double fusion, subjects should perceive no change in non-fixation feature depth when the fixation feature disappears. Therefore, throughout Experiment 2, subjects reported whether the non-fixation feature' s depth changed after the fixation feature disappeared.

4.1 Method

4.1.1 Subjects Ten subjects from Experiment 1A participated (5 males, 5 females), aged 19–26 years (mean age = 22.70 ± 2.33 years). One additional subject from Experiment 1A was unable to participate.

4.1.2 Apparatus Identical to Experiment 1A.

4.1.3 Stimuli Stimuli included three types: Panum stimuli and Type I and Type II control stimuli. In these configurations, broken lines could appear on either the left or right side of the straight line, with left-right eye presentation alternated across trials, yielding 4 conditions for each stimulus type. To avoid interference, we designated the large broken line as the fixation feature and the small broken line as the non-fixation feature. Two red markers appeared above and below the large broken line vertex in images presented to left and right eyes (Figure 6 [Figure 6: see original paper]), primarily to control vergence (Gillam et al., 1999; Wang et al., 2001). Thus, one eye saw only the upper marker while the other saw only the lower marker.

Figure 6 shows stimuli used in Experiment 2. Figure 6A depicts Panum stimuli. Figure 6B shows Type I control stimuli, where after large broken line disappearance, the stimulus in Figure 6D appears, and subjects should report no depth change in the small broken line. Figure 6C shows Type II control stimuli, where after large broken line disappearance, subjects should report a depth change in the small broken line. Figure 6D shows the stimulus after fixation feature (large broken line) disappearance.

As shown in Figures 6B and 6C, Type I and Type II control stimuli present both large and small broken lines with definite corresponding retinal images in both eyes. In these stimuli, the large broken line always serves as the fixation feature with zero disparity, while the small broken line' s disparity varies. Using the example where the first column image is presented to the left eye and the second column to the right eye: in Type I control stimuli, the non-fixation feature (small broken line) has +0.3 arcmin disparity, and after fixation feature (large broken line) disappearance, the stimulus in Figure 6D appears, maintaining +0.3 arcmin disparity for the small broken line. In Type II control stimuli, the non-fixation feature (small broken line) has -0.3 arcmin disparity, and after fixation feature disappearance, the same Figure 6D stimulus appears, but now the small broken line' s disparity becomes +0.3 arcmin. According to binocular disparity processing mechanisms, for Type I stimuli, subjects should report no depth change in the small broken line after large broken line disappearance; for Type II stimuli, subjects should report a depth change.

4.1.4 Procedure The procedure is illustrated in Figure 7 [Figure 7: see original paper]. Each trial began with a straight line containing a red fixation dot for 300 ms. Two red markers then appeared on one side of the line with unlimited presentation duration. After subjects aligned the upper and lower markers, they pressed the spacebar, triggering 200 ms stimulus presentation. Subsequently, the large broken line disappeared while subjects maintained gaze at its location without attempting to shift gaze to the small broken line. The stimulus containing only the small broken line then presented for 100 ms, after which subjects reported via keypress whether the small broken line' s depth had changed. After responding, the red fixation dot reappeared at the straight line' s center, and subjects redirected gaze to begin the next trial.

The experiment included a practice block and 2 formal blocks. In practice, each condition was presented randomly twice. In each formal block, the 4 Panum stimulus conditions were presented randomly 10 times each, and the 8 Type I and Type II control stimulus conditions were presented randomly 10 times each, yielding 120 trials per block and 240 trials total. Subjects could rest between blocks.

4.2 Results

For Panum and Type I/II control stimuli, no significant differences existed in depth perception results when broken lines appeared on the left versus right side, so these conditions were combined. Additionally, for the same reasons as in Experiment 1A, results from left-right eye presentation alternation were combined. Final results are shown in Figure 8 [Figure 8: see original paper].

A one-way within-subjects ANOVA was performed on the probability of subjects reporting no depth change in the small broken line. Results showed a significant main effect of stimulus type, $F(1, 10) = 515.89$, $p < 0.001$, $\text{p}^2 = 0.98$. Post-hoc comparisons indicated that for Panum stimuli, the probability of reporting no depth change in the small broken line after large broken line disappearance was slightly lower than for Type I control stimuli. However, a significant difference existed between Panum stimuli and Type II control stimuli ($p < 0.001$). After large broken line disappearance, subjects reported significantly higher probabilities of no depth change in Panum stimuli compared to Type II control stimuli. These results indicate that Panum stimuli differed significantly from Type II control stimuli and were more similar to Type I control stimuli.

Figure 8 shows that in Panum stimulus conditions, the probability of perceiving no depth change in the non-fixation feature after fixation feature disappearance exceeded 90%. This demonstrates that non-fixation feature depth perception does not originate from depth contrast, indicating that depth perceived in Panum' s limiting case is not generated by depth contrast.

General Discussion

Analysis of previous research reveals persistent opposing viewpoints supporting and opposing double fusion regarding the depth origin in monocular regions (Kumar, 1996; Ono, Shimono, & Shibuta, 1992). This study employed fold-line Panum stimuli with slant effects and clear criteria to investigate whether depth perception results in Panum stimuli originate from double fusion or unique fusion.

5.1 Evidence for Double Fusion

Experiment 1A results demonstrated that subjects could correctly perceive fixation feature depth under both Panum and control stimulus conditions. Experiment 1B results showed that consistent probability between perceived depth and expected depth for non-fixation features was significantly higher than chance under both stimulus conditions, indicating correct depth perception of non-fixation features. Combined with Experiment 1A results, these findings show that subjects could perceive depth in both fixation and non-fixation features under both stimulus conditions. These results support double fusion, demonstrating that after binocular fusion of fold-line Panum stimulus configurations, subjects perceive depth in the planes containing both features.

Comparative analysis of Experiments 1A and 1B reveals several issues worth discussing. First, the significant main effect of stimulus type on consistent probability in both experiments showed lower consistent probability for Panum stimuli than control stimuli, indicating greater difficulty perceiving depth in Panum stimuli. This may occur because control stimuli contain two features in both eyes, allowing definite correspondence and matching for each feature, whereas in Panum stimuli, uncertainty exists regarding which of the paired features matches with the single feature, making depth perception more difficult.

Second, as shown in Figures 3 and 5, consistent probability for non-fixation features was significantly lower than for fixation features under both stimulus conditions, indicating greater difficulty perceiving non-fixation feature depth. This occurs because for fixation features, subjects fixate on the feature during presentation and report its depth afterward. For non-fixation features, subjects must maintain gaze on the fixation feature during presentation while reporting the non-fixation feature’ s depth after offset. Under strict fixation control, subjects can only report non-fixation feature depth unconsciously through sensation and guessing, increasing judgment difficulty.

Finally, for both Panum and control stimuli, consistent probability was significantly lower when fixation features were small broken lines compared to large broken lines, indicating greater difficulty perceiving small broken line depth. This may result from disparity gradient effects. Although small and large broken lines had equal heights, their horizontal widths differed, creating different horizontal disparity gradients. In stereopsis, binocular fusion is constrained not only by disparity but also by disparity gradient, with larger gradients increasing fusion difficulty (Brookes & Stevens, 1989). The small broken line’ s larger horizontal disparity gradient made its depth perception more difficult.

5.2 Non-Fixation Feature Depth Does Not Originate from Depth Contrast

Although previous studies have frequently observed double fusion in occlusion configurations (Harris & Wilcox, 2009), such results have sometimes been questioned. For instance, researchers designed a variant of Panum’ s limiting case demonstrating that a single feature presented to one eye could fuse with both features presented to the other eye, supporting double fusion. Gillam et al. (1999) subsequently used similar stimuli presenting one straight line to one eye and two intersecting oblique lines to the other eye, with results also supporting double fusion in Panum’ s limiting case (Gillam et al., 1999). However, later researchers suggested these perceptual results could also arise from depth contrast, challenging double fusion to some extent. Depth contrast refers to a feature without intrinsic depth appearing to have depth in the opposite direction of an adjacent depth-defined feature (Howard & Rogers, 2012). To date, researchers remain uncertain whether double fusion results originate from depth contrast.

For fixation features in Panum stimuli, depth from feature matching is widely accepted, so 质疑 primarily target non-fixation features. Experiments 1A and 1B demonstrated that subjects could correctly perceive depth in both fixation and non-fixation features in Panum stimuli. Building on these findings, Experiment 2 results showed that after fixation feature disappearance, the probability of perceiving no depth change in non-fixation features exceeded 90% in Panum stimulus conditions. This indicates that non-fixation feature depth perception does not originate from depth contrast, demonstrating that depth perceived in Panum’ s limiting case is not generated by depth contrast. These findings refute previous 质疑 that perceptual depth results from depth contrast and provide new evidence supporting double fusion as the origin of depth in Panum’ s limiting case.

5.3 Advantages of Fold-Line Panum Stimulus Configuration

Previous studies using different stimulus configurations have reached different conclusions: Panum line and Gillam curve configurations support double fusion, while Frisby wave line and Wang oblique line configurations support unique fusion. Researchers may have introduced confounding factors when using different configurations, leading to inaccurate and unstable perceptual results. The fold-line stimulus configuration used in this study offers several advantages over other commonly used configurations, accommodating both perceptual accuracy and stability (Gettys & Harker, 1967).

Specifically, for stereopsis with unequal numbers of features between eyes, smaller differences between features yield more stable perceptual results and less influence from diplopia or binocular rivalry during fusion. However, smaller differences make it more difficult for observers to discriminate between perceptual results caused by double fusion, sometimes leading to ambiguous or equivocal situations that affect accuracy. Fold-line stimulus configurations largely resolve these issues. Since slant of the broken line plane constitutes an independently perceivable stereoscopic effect, it can serve as a criterion for determining whether fusion occurs directly (Lee & Dobbins, 2002; Wang, Wu, Ni, & Wang, 2001). Moreover, the similar physical properties of broken lines presented to both eyes enhance perceptual stability (Li et al., 2011).

This study investigated the double fusion depth mechanism in Panum' s limiting case using fold-line Panum stimuli with slant effects and clear criteria. Results demonstrate that the depth perception mechanism in Panum' s limiting case involves double fusion: subjects correctly perceive depth in both fixation and non-fixation features, and these depth perception results originate from double fusion rather than depth contrast. These findings resolve previous controversies and provide a theoretical foundation for establishing new stereoscopic matching models.

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Note: Figure translations are in progress. See original paper for figures.