A reevaluation of the tolerance to vertical misalignment in stereopsis

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The stereoscopic system tolerates some vertical misalignment of the images in the eyes. However, the reported tolerance for an isolated line stimulus (~4°) is greater than for a random-dot stereogram (RDS, ~45 arcmin). We hypothesized that the greater tolerance can be attributed to monoptic depth signals (E. Hering, 1861; M. Kaye, 1978; L. M. Wilcox, J. M. Harris, & S. P. McKee, 2007). We manipulated the vertical misalignment of a pair of isolated stereoscopic dots to assess the contribution of each depth signal separately. For the monoptic stimuli, where only one half-image was present, equivalent horizontal and vertical offsets were imposed instead of disparity. Judgments of apparent depth were well above chance, though there was no conventional disparity signal. For the stereoscopic stimuli, one element was positioned at the midline where monoptic depth perception falls to chance but conventional disparity remains. Subjects lost the depth percept at a vertical misalignment of between 44 and 88 arcmin, which is much smaller than the limit found when both signals were provided. This tolerance for isolated stimuli is comparable to the reported tolerance for RDS. We conclude that previous reports of the greater tolerance to vertical misalignment for isolated stimuli arose from the use of monoptic depth signals.

Keywords: stereopsis, stereo matching, vertical misalignment, monoptic depth

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Introduction

Tolerance to vertical misalignment

Binocular stereopsis requires that the retinal images in the two eyes be matched to allow detection of horizontal disparity. In most computational models, this matching process is constrained to occur along the horizontal dimension or along epipolar lines (Marr & Poggio, 1976; Poggio & Poggio, 1984). The human stereoscopic system tolerates some vertical misalignment of the images, presumably to maintain robust depth perception in spite of slight vertical misalignment of the two eyes, imperfections in retinal shape, and vertical disparities that occur outside the horopter. Reported tolerance to vertical misalignment ranges from less than 10 arcmin (Nielsen & Poggio, 1984; Prazdny, 1985; van Ee & Schor, 2000) to 4° (Mitchell, 1970) depending on stimulus features and experimental conditions.

Ogle (1954) reported robust stereoscopic depth percepts in the presence of large vertical disparities of up to 25 arcmin in small point stimuli. Tolerance to vertical misalignment was reduced when a standing disparity was introduced between the test stimulus and fixation plane. In a later study, Mitchell (1970) used a pair of isolated vertical lines with a large horizontal disparity of 2.75° to assess the tolerance of stereopsis to vertical misalignment. Vertical misalignment as high as 4° was tolerated. He proposed that this resilience to large vertical misalignment was due to his use of very large horizontal disparities.

Ogle and Mitchell used isolated targets (dots or lines). In experiments using random-dot stereograms (RDS), very different results have been reported. For instance, Nielsen and Poggio (1984) reported that tolerance to vertical misalignment in processing depth from horizontal disparity in RDS patterns was only 3.5 arcmin. Similarly, Prazdny (1985) reported an upper limit of 10 arcmin. More recently, Stevenson and Schor (1997) proposed that the relatively small tolerances found in those two studies

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were due to the small area of their stimuli. They showed that the tolerance to vertical misalignment could be up to 45 arcmin in a dynamic random-dot stereogram with a diameter of 12°.

The differences in the reported tolerance of stereopsis to vertical misalignment could be attributed to the fact that isolated line or dot stimuli and RDS support different ranges of horizontal disparities. Isolated line stimuli generate depth percepts over a large range of horizontal disparities well outside Panum's fusion zone, where the stimuli appear diplopic (Ogle, 1952). Regions in RDS with horizontal disparities that are large relative to the element size are not perceived as diplopic (Fender & Julesz, 1967) and do not provide reliable depth percepts. When RDS contain disparities outside the fusion range, there is a high probability of false matches, resulting in ambiguous depth percepts. van Ee and Schor (2000) showed that matching ambiguity in oblique lines influences the vertical operating range for horizontal disparity processing. If the large tolerance to vertical misalignment reported by Mitchell was due to his use of very large horizontal disparities in single isolated patterns, it is not surprising that the upper limit of vertical misalignment was not replicated with RDS.

Monoptic depth

Monoptic depth perception may influence stereoscopic tolerance to vertical misalignment and could be responsible for the large differences in reported tolerance.

Consider the images formed by two vertical bars lying at different distances in the midline, as shown in Figure 1a.

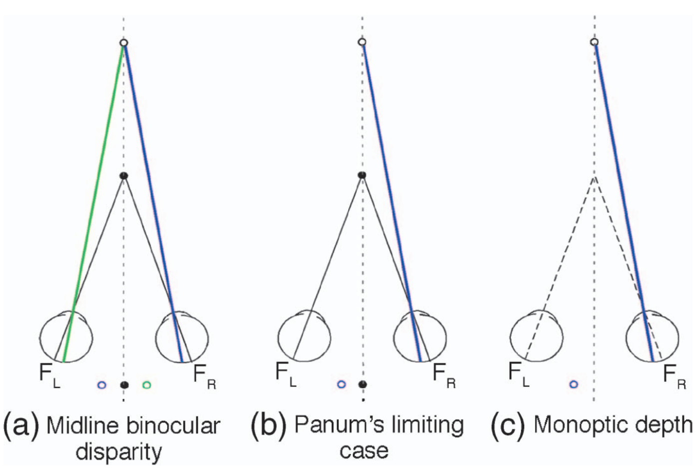

Figure 1. (a) Midline disparity. A far midline object projects images to each nasal retina. (b) Panum's limiting case. A monocular image on the nasal side of the image of a binocular object creates the impression of an object beyond the binocular object. (c) Monoptic depth. A monocular image on the nasal side of a retina creates the impression of an object beyond the plane of convergence.

When the eyes are converged on the near bar, each image of the far bar lies on the nasal side of the retina. Furthermore, the images project to opposite cerebral hemispheres and are separated by the fused image of the near bar. When the eyes are converged on the far bar, each image of the near bar lies on the temporal half of the retina. Thus, two matching monocular images falling on the nasal retinas invariably indicate an object beyond the fixation plane and two monocular images on the temporal retinas indicate an object nearer than the fixation plane. When one monocular image is removed, as in Figure 1b, the stimulus conforms to Panum's limiting case, which is defined as a monocular bar to one side of a binocularly fused bar. A monocular bar on the nasal side of the binocular bar appears beyond the binocular bar and a monocular bar on the temporal side appears nearer than the binocular bar. Thus the visual system interprets the depth of a monocular stimulus in terms of its retinal location relative to the point of fixation. This could be an innate mechanism, but visual experience over a lifetime confirms that a monocular image on the nasal retina arises from an object beyond where we are fixated and that one on the temporal retina arises from an object nearer than where we are fixated. If the visual system embodies this ecologically valid rule, then a monocular image on the nasal retina should appear more distant than a monocular image on the temporal retina even when there are no other objects in view. Wilcox, Harris, and McKee (2007) introduced the term "monoptic depth" to describe the depth percept created by a monocular stimulus in one eye while the other eye views a blank field.

Hering (1861) was the first to propose that an image on the temporal retina of one eye will appear to lie *in front of* the fixation plane, and an image on the nasal retina appears to lie *beyond* the fixation plane. According to Hering, the perceived depth increases with increasing horizontal distance of the image from the fovea. This relationship between the positions of a monocular image and its perceived depth signs corresponds to the analysis presented above. Helmholtz (1910) ridiculed this notion citing numerous examples where the theory would fail. However, Kaye (1978) showed that depth percepts could be obtained from monoptic images, thus confirming Hering's theory.

Wilcox et al. (2007) replicated and extended Kaye's experiments. They found that the monoptic depth percept disappeared when the unstimulated eye was patched, and that shifting the fixation point away from the midline reversed perceived depth due to the shift in the retinal location of the stimulus. These results suggest that the monoptic depth is a binocular phenomenon. They went on to show that the monocular image is likely matched to the fovea of the unstimulated eye using a stereoscopic mechanism that is able to match dissimilar features, or contrast envelopes, in the two eyes.

The motivation for the experiments reported here is our observation that the conditions under which tolerance to large vertical misalignment has been reported are also conditions under which monoptic depth can be perceived. In Mitchell's (1970) study, the half-images of the stereogram were positioned symmetrically about the fixation point, so that each half of the stereo pair fell on the temporal retina when the images had crossed disparity. According to the monoptic depth literature (Hering, 1861; Kaye, 1978; Wilcox et al., 2007), this configuration will produce a percept of 'near.' Similarly, when the stimulus disparity was uncrossed in Mitchell's study, the images fell on the nasal retinas, producing a percept of 'far.' It is possible that the reportedly large tolerance to vertical misalignment reflects the influence of a monoptic depth mechanism, which does not involve matching the vertically offset stimuli. Instead, each half-image provides a separate monoptic depth signal (Figure 2). Thus, the stimulus consists of two monoptic depth signals with the same depth sign. In contrast, monoptic depth could not be a factor in Ogle's (1954) experiments because he used a very small horizontal disparity. He measured the range of vertical misalignment over which stereoacuity was as great as with vertically aligned stimuli. His graphs show that the critical stereoacuity was about 0.5 arcmin^{-1} or higher, which corresponds to a horizontal disparity of 2 arcmin or less. Monoptic depth perception is less precise than stereopsis and falls to chance for stimuli with less than approximately 7 arcmin eccentricity from the fovea (Wilcox et al., 2007). In spite of the geometric similarities of the stimulus conditions in Mitchell's (1970) study and those in the limited monoptic depth literature (Hering, 1861; Kaye, 1978; Wilcox et al., 2007), there has been no previous attempt to link these phenomena. Other investigators have suggested that the large differences in the reported tolerance for vertical disparity are due to differences in the size and spatial frequency of the stimuli (Stevenson & Schor, 1997) or to ambiguities in matching the images in the two eyes (van Ee & Schor, 2000). It is important to note that such explanations depend on the images in the two eyes being matched, whereas monoptic depth requires only a single half-image presented to one eye.

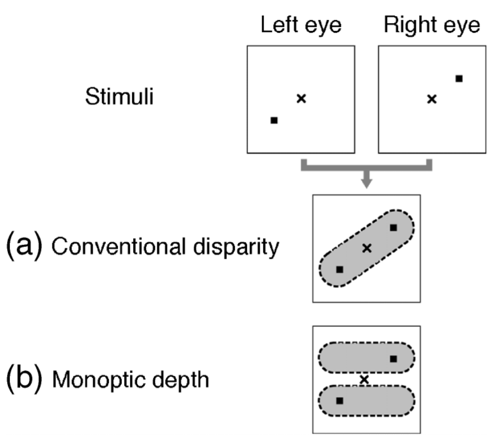

Figure 2. This schematic illustrates the differences between the conditions tested in Experiment 1. The upper row depicts the left and right eyes' stimulus. The two lower boxes show the potential matches according to conventional binocular disparity processing (middle box) vs. monoptic depth (lower box). 'x' indicates the position of the fixation point, which disappeared before the stimuli appeared in our experiments. We have depicted the 'match' as a shaded oval region outlined by a broken line. The important difference between the two accounts is the presence of (a) a single binocular match vs. (b) two separate monoptic matches.

To assess whether monoptic depth underlies the large tolerance to vertical misalignment in isolated stimuli, we measured the perceived depth of a pair of small stereoscopic dots with a large horizontal disparity and variable vertical misalignment. First, we replicated Mitchell's (1970) results with and without a horizontal line positioned between the pair of dots and extending across the display. Second, we repeated this experiment with only one dot present, so that there was no conventional disparity signal, but the monoptic signal remained. Third, we shifted the stereoscopic pair so that one of the dots was positioned at the midline where monoptic depth percepts fall to chance, leaving only the conventional binocular disparity signal.

General methods

Apparatus

Stereoscopic images were presented on a pair of flat-screen monitors arranged in a Wheatstone mirror stereoscope with a fixed viewing distance of 57 cm. The monitors were placed face to face and viewed through a pair of mirrors oriented at ±45°. The observer sat with his/her head in a chinrest. The room was dark and responses were made using a computer keyboard.

Stimuli

Test stimuli were square dots subtending approximately 9×9 arcmin and a horizontal disparity of 88 arcmin (selected to maximize apparent depth in pilot experiments using the same stimuli) and a variable vertical misalignment (Figure 3c). A fixation point (9×9 arcmin) and a pair of nonius lines (22×4.4 arcmin) were visible prior to each trial to anchor vergence (Figure 3a). The nonius lines were positioned 22 arcmin above and below the fixation point. The upper and lower regions of the display contained a random array of crosses, presented binocularly at zero disparity. The cross-filled regions were separated from the test area by two horizontal lines above and below the test area at a distance of 6.5° from the fixation point. The crosses and the lines extended to the

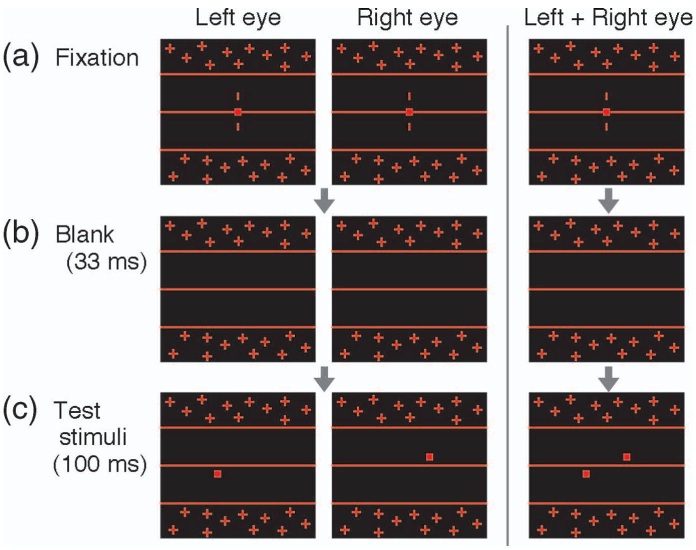

Figure 3. The stereo pairs in the left and center columns depict a time line (from a to c) of stimulus presentation and the right column shows the combined binocular (non-stereoscopic) view. (a) The central dot is the fixation point and the small vertical lines, one in each eye, are nonius lines. The upper and lower cross-filled regions are always present to ensure stable vergence. (b) There was a blank interval after the fixation point disappeared. (c) Test stimuli consisted of a pair of diplopic dots with a fixed horizontal disparity and variable vertical misalignment. The horizontal line at the center of the display was presented only on some trials in Experiment 1.

edge of the screen. These peripheral features ensured that vergence remained stable within and across trials (Burian, 1939; Houtman & van der Pol, 1982). The stimuli were presented using only the red channel of the display, and their luminance was 3 cd/m^2. They were presented against a black background with a luminance of 0.01 cd/m^2 (as measured through the mirror).

On some trials, test stimuli were separated by a horizontal binocular line (1 arcmin thick), which extended the full width of the display (Figure 3). This line bisected the display and was equidistant from the two half-images of the test stimuli. If depth percepts from vertically offset horizontally disparate stimuli are due to conventional disparity matching, then the presence of the horizontal line between the stereo pairs should disrupt stereo matching. Conversely, if the depth percept is monoptic in nature, then the horizontal line will have no such effect.

Procedure

Figure 3 shows the time line for a single trial. At the beginning of each trial, the fixation point and nonius lines were visible along with the vergence locks in the upper and lower regions of the display. When the nonius lines appeared collinear, the subject pressed a button and the fixation and nonius lines disappeared. Then, after a 33-ms blank interval, a test stimulus was presented for 100 ms. This presentation time was short enough to ensure that no eye movements were initiated in response to the test stimulus while it was visible. The subject's task was to judge the depth of targets as "near" or "far" relative to the remembered position of the fixation point by pressing the appropriate arrow keys on a keyboard.

Subjects

All three experiments involved four observers with normal or corrected-to-normal visual acuity. Pilot testing showed that they all perceived consistent stereoscopic depth for crossed and uncrossed horizontal disparities of 0.15 to 1.5 arcmin relative to a fixation point that had zero vertical disparity. Two observers were authors, and the other two were unaware of the purpose of the experiment.

Experiment 1

The primary aim of Experiment 1 was to replicate Mitchell's (1970) experiment. In addition, we evaluated the likelihood that a conventional horizontal disparity mechanism was involved. This was done by including a condition in which a horizontal binocular line between the two half-images extended the full width of the screen.

Methods

As described in the General methods section, the target was a diplopic pair of dots with a crossed or uncrossed horizontal disparity of 88 arcmin and variable vertical misalignment. On each trial, subjects judged the apparent depth of the target relative to the fixation plane. As expected, although the stimuli were diplopic, observers reliably reported a consistent percept of depth with both half-images apparently displaced in the same direction.

The vertical displacement of the target images was manipulated using an interleaved staircase procedure. The vertical offset was decreased following incorrect responses and increased after correct responses by a constant step size of 8.8 arcmin. There were eight stimulus conditions corresponding to all combinations of the following conditions: sign of vertical misalignment (right above or left above), sign of horizontal disparity (crossed or uncrossed disparity), and two horizontal divider conditions (present or absent). Eight sequences representing these stimulus conditions were randomly interleaved in a single session. Each sequence was completed when the number of reversals reached 10; under these conditions, the average of the last 6 reversals

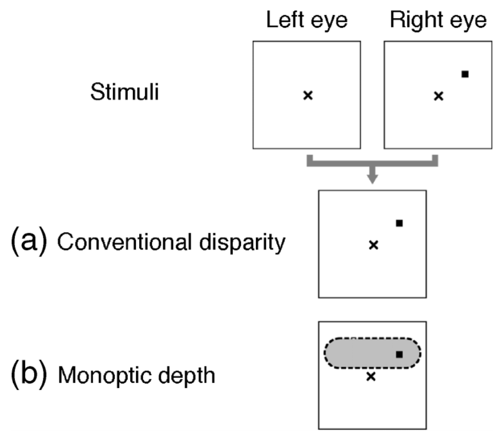

Figure 4. This figure follows the same convention as Figure 2, but illustrates the depth information present in Experiment 2, when one of the pair of line targets is removed. Note that now in (a) there is no binocular disparity match, but as shown in (b) there is a single monoptic signal.

was taken to be the point at which the observer lost depth perception. Importantly, we also ended a test sequence when the vertical offset reached 3°, which was the upper end of the range possible using our configuration and apparatus. A given session continued until all of eight sequences were completed.

Results and discussion

In all test conditions, and for all subjects, the vertical offset between the half-images reached 3°. Thus, as reported by Mitchell (1970), the upper vertical misalignment limit for discriminating depth sign was at least 3°.

The fact that the horizontal line had no effect on the percept of depth in this experiment suggests that depth percepts were not due to conventional stereoscopic matching. However, the horizontal line may not have completely disrupted horizontal disparity matching. In Experiment 2, we directly assessed the contribution of monoptic depth to the percept of depth in Experiment 1, by eliminating the possibility of using conventional stereoscopic matching.

Experiment 2

Our aim here was to eliminate conventional stereoscopic depth information but leave a monoptic depth signal intact. To do this, we used the stimulus described in Experiment 1 but removed one of the half-images. The resulting stimulus was similar to the monoptic targets used by Wilcox et al. (2007) except that our stimuli were vertically offset from the fixation point. The unstimulated eye on any trial viewed a blank screen with the same mean luminance as the display with the monoptic target.

Methods

The stimuli were the same as in Experiment 1 except in the monoptic depth condition, in which only one of the stereoscopic half-images was presented as a target (Figure 4). The target was positioned in one of four quadrants relative to the fixation point (above, below, left, right). The horizontal and vertical offsets from the center were fixed at 44 arcmin and 22 arcmin, respectively. In the stereoscopic condition, a pair of stereoscopic dots was presented binocularly and positioned symmetrically about the fixation point (as in Experiment 1). The observer judged the apparent depth of the target dot or dots, relative to the remembered position of the fixation point.

There were eight stimulus conditions corresponding to every combination of two viewing conditions (stereoscopic or monoptic condition), two directions of vertical offset (above or below of the fixation point), and two directions of horizontal offset (nasal or temporal retina). These conditions appeared in random order using the method of constant stimuli and were repeated 5 times.

Results and discussion

Figure 5 plots the proportion of trials in which the target was seen as lying behind the fixation plane, for each stimulus condition and all observers. We have collapsed across the vertical offset directions as there was no difference between these conditions. Dark gray and white bars show the results for binocular targets with crossed and uncrossed disparity, respectively. Black and light gray bars show the results for the monoptic targets positioned on the temporal and nasal retina, respectively. Clearly, there is a significant effect of the location of the stimuli on

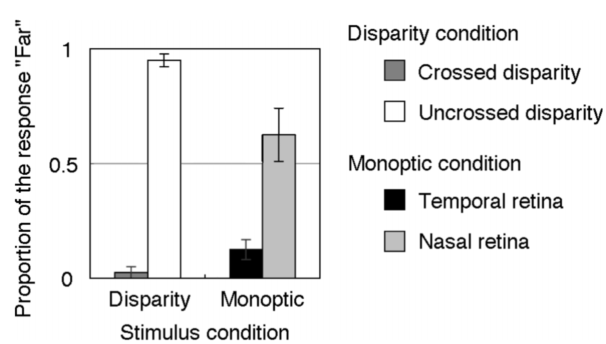

Figure 5. Results of Experiment 2 for both conditions (disparity vs. monoptic). Open and shaded bars represent conditions in which the target was on the nasal and temporal retina, respectively. Error bars show ±1 *SEM*.

the retinas (ANOVA; $F(1, 3) = 373.36$, $p < 0.01$ in disparity condition; $F(1, 3) = 10.91$, $p < 0.05$ in monoptic condition). That is, targets positioned on the nasal retina (or with uncrossed disparity) were perceived as lying beyond the fixation plane while targets positioned on the temporal retina (or with crossed disparity) were perceived as lying in front of the fixation plane. This pattern of results is consistent with the presence of monoptic depth as reported by Kaye (1978) and Wilcox et al. (2007). Importantly, taken together with Experiment 1, these data suggest that the percept of depth reported by Mitchell (1970) was due to the diplopic targets stimulating the monoptic depth mechanism. Thus, Mitchell's results cannot be considered evidence for an extremely high tolerance to vertical misalignment in the horizontal disparity system.

Although the subjects reliably perceived depth in the monoptic conditions in Experiment 2, performance was poorer than in the binocular (stereoscopic) condition. One explanation for this degradation is that the stereo pair in the binocular conditions consisted of two monocular dots signaling the same monoptic depth, while the monoptic conditions tested in Experiment 2 consisted of only one dot per trial. Thus the monoptic signal in the binocular conditions was either twice as strong or the enhanced performance was due to probability summation of two monoptic depth signals. In addition, the task was difficult because subjects had to report the target's depth sign after the target had been removed. This might be one source of variability in the data.

Experiment 3

Experiment 1 has shown that depth is reliably perceived from stereoscopic targets with a large horizontal disparity in the presence of vertical misalignment. Experiment 2 has shown that when horizontal disparity is removed, reliable depth is still perceived; these results point to monoptic depth as a basis for the percepts previously thought to be due to tolerance to vertical misalignment in the stereoscopic system. However, our findings do not exclude the possibility that there is some contribution of horizontal disparity to the depth percept with large vertical misalignments. Therefore in Experiment 3, we designed a set of conditions to determine if there is any contribution of horizontal disparity to depth judgements under conditions of vertical misalignment. To do this, we capitalized on the fact that monoptic depth percepts fall to chance when the test stimulus is presented at the midline (see Figure 6). If the depth of a centrally positioned target is properly discriminated, the percept must be due to horizontal disparity processing. On the other hand, if reliable depth percepts are lost, then we can safely conclude that there is little or no stereoscopic tolerance to vertical misalignment, and that the depth percepts in Experiment 1 are due solely to monoptic depth.

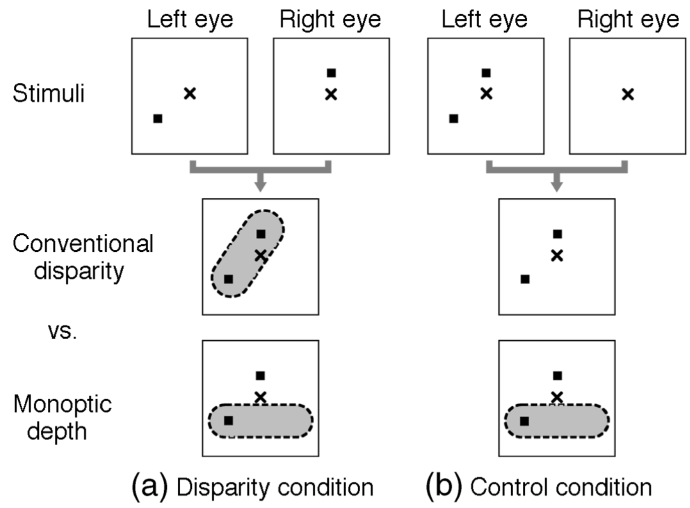

Figure 6. The potential depth information available in Experiment 3 is shown here using the conventions of Figure 2. In the (a) disparity condition, one of the line stimuli is always presented at the midline and is used as the target. The other line is presented on the nasal or temporal retina. Note that there is a horizontal disparity match but no monoptic signal for the target line. In the (b) control condition, both lines are presented to one eye. In this case, there is no horizontal disparity match available to the midline target.

Methods

The stimuli were essentially the same as those used in Experiments 1 and 2 except for the position of the targets. The test stimulus was a diplopic pair of dots one of which was on the midline and the other at some vertical/horizontal offset relative to it (see Figure 6). Subjects were told to judge the location in depth of the midline elements and to 'ignore' the peripheral dot. Note that on all trials a stereoscopic pair of dots was present, so if horizontal disparity processing could be used to do the task, it would be available. However, since monoptic depth falls to chance at the midline (Wilcox et al., 2007) observers would not be able to perform above chance if they were relying on monoptic signals.

We were aware that on monoptic trials the partner (peripheral) dots could produce monoptic depth percepts and influence the perceived depth of the central element via depth capture or contrast. To assess the presence of such effects, we added control conditions in which the target and partner dots were presented to the same eye (Figure 6). In these conditions, horizontal disparity would not be defined, and we could identify the occurrence of depth capture and contrast.

There were 16 stimulus conditions. For disparity conditions, there were two directions of horizontal disparity, two directions of vertical misalignment, and two target-eye conditions (target (midline) dot in right eye and partner (peripheral) dot in left or vice versa). Our control conditions, in which both elements appeared in the same eye, included two target-eye conditions (right or left eye), two partner dot positions (temporal retina or nasal retina), and two vertical dot positions (target above or below the partner). All conditions appeared in random order and each of them was repeated five times. The vertical offset between the target and the partner dot was either 44 arcmin or 88 arcmin but held constant within a session. The horizontal offset between the target and the partner dots was constant at 88 arcmin, which is the same as in Experiment 1.

Results and discussion

Figure 7 shows the proportion of trials in which the target was seen as lying behind the fixation plane, for each condition and all observers. The dark gray and white bars in disparity conditions show the results for targets with crossed disparity and with uncrossed disparity, respectively. The black and light gray bars in monoptic conditions show the results when the partner dot was placed on the temporal and nasal retina, respectively, so that a significant effect of the location of the partner dot means the occurrence of depth capture or depth contrast.

The data depicted in Figure 7 exhibit a strong dependence on vertical separation. For disparate stimuli subjects could discriminate the direction of depth at 44 minutes of arc. They reported uncrossed disparities as "far" significantly more than crossed disparities ($F(1, 3) = 24.44$, $p < 0.05$). Furthermore, crossed disparities were most frequently judged near and uncrossed as far. Thus we can conclude that processing of horizontal disparity tolerates vertical image misalignment of up to 44 arcmin, for stimuli of this size. However, at 88 arcmin vertical separation subjects were no longer sensitive to disparity ($F(1, 3) = 0.25$, $p > 0.10$) and both crossed and uncrossed stimuli were responded to at chance levels (50%). Recall that the prediction for this experiment was that if responses were based on only monoptic depth, observers would be unable to make reliable depth judgements. Therefore, it appears that, for our stimuli, the horizontal disparity mechanism tolerates vertical misalignments of 44, but not 88 arcmin.

This conclusion is based on the assumption that the monoptic depth of the partner stimulus had no effect. Analysis of the control conditions indicated that subjects performed at chance levels for all conditions. The fact that there was no effect of partner dot position in monoptic conditions ($F(1, 3) = 0.04$, $p > 0.10$ at a vertical separation of 44 arcmin; $F(1, 3) = 2.58$, $p > 0.10$ at a vertical separation of 88 arcmin) shows that the results with the disparate stimuli are not due to monoptic depth capture or contrast effects.

The control data do show that one of the four observers' responses at 44 and 88 arcmin vertical separation were influenced by the perceived depth of the partner (non-target) dot. For this observer, the perceived depth of the central element shifted away from the depth of the peripheral element, in the direction opposite to that predicted by disparity processing. This observer showed strong monoptic depth in other trials so this result is not surprising and does not effect our conclusion. However, it is interesting that the percepts obtained from monoptic stimuli can be strong enough to induce depth percepts in otherwise ambiguous stimuli.

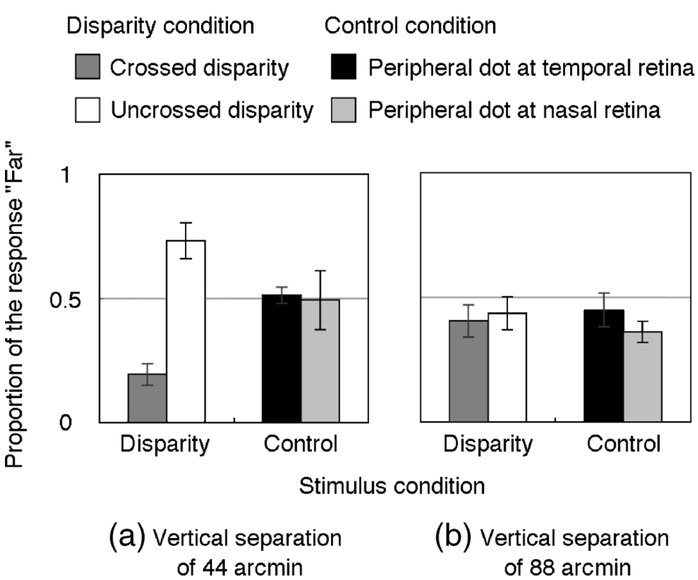

Figure 7. Results of Experiment 3 are shown for the stimuli with vertical separations of 44 and 88 arcmin. Open/solid and shaded bars represent conditions in which the partner dot was positioned on the nasal and temporal retina, respectively. Error bars show ±1 *SEM*.

General discussion

We have shown that the perceived depth of stereoscopically viewed elements with vertical misalignment is determined not only by the horizontal disparity between the dots but also by the retinal position of each element. This result is consistent with existing literature on monoptic depth (Kaye, 1978; Wilcox et al., 2007) and has important implications for experiments in which diplopic targets are used to assess stereopsis.

One such area of research is the tolerance of horizontal disparity processing to vertical image misalignment. We found that when monoptic depth was eliminated, horizontal disparity processing could tolerate a maximum vertical misalignment between 44 arcmin and 88 arcmin. This tolerance is much smaller than that reported by Mitchell (1970). However, it seems likely that monoptic depth signals were available in his stimuli, because the stimuli had disparities well beyond the fusion range and the half-images were not at the fovea (Wilcox et al., 2007).

As mentioned previously, isolated line stimuli generate depth percepts over a large range of horizontal disparities well outside Panum's fusion area, where the stimuli appear diplopic (Ogle, 1952). In contrast, RDS with horizontal disparities that are large relative to the element size do not appear diplopic (Fender & Julesz, 1967) and do not provide reliable depth percepts. It is not likely that this difference is due to a basic difference between line stereograms and RDS, since, by eliminating the monoptic depth signals, we obtained tolerance limits with isolated stimuli that were very similar to those reported by Stevenson and Schor (1997) with RDS. The transition from a coarse to a fine operating range with the removal of monoptic depth is consistent with Wilcox et al.'s argument that monoptic depth reflects a mechanism that provides reliable depth information in spite of large differences between retinal images in the two eyes. To evaluate depth percepts produced by disparity matching between a pair of stereoscopic images, it is important to consider the effect of monoptic depth produced by each half-image of a stereoscopic pair.

We conclude that stereoscopic processing of a single pair of horizontally disparate lines tolerates substantial vertical misalignment. The limit of tolerance is comparable to the limit found by Stevenson and Schor (1997) with large dynamic random dot stereograms. The limit is much smaller than that reported by Mitchell (1970) with stimuli similar to ours. We have shown that the discrepancy in the reported tolerance to vertical misalignment is due to the operation of two distinct disparity mechanisms. A precise short-range mechanism processes conventional disparities from nearly aligned dichoptic features. A coarse binocular system with properties we are just beginning to fully understand can produce reliable disparity judgments in the presence of extremely large vertical misalignments.

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