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Real 3D increases perceived depth over anaglyphs but does not cancel stereo-anomaly

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ABSTRACT

Background: About 30% of the population has difficulties detecting the sign and the magnitude of binocular disparity in the absence of eye movements, a phenomenon called stereo-anomaly. The stereo-anomaly tests so far are based on disparity only (e.g. red–green stereograms), which means that other depth cues cannot be used and even provide conflicting depth information.
Objective: Here we investigate whether stereo-anomaly also occurs using a "true-3D" display which provides other depth cues that are all consistent with one particular distance in depth. Secondly, we examine differences in depth perception between red–green (anaglyphic) and true-3D displays. Finally, we test the displays' relative viewing comfort.
Method: Sixteen observers (four of which were stereo-anomalous) judged the distance in depth between a fixation square and one or two bars. They were presented on an anaglyphic and a true-3D display, both in the fovea and 5 deg in the visual periphery. Observers were asked about the viewing comfort of both displays.
Results: Stereo-anomalous observers also showed difficulties in perceiving depth with the true-3D display. Yet the true-3D display increased the perceived depth range compared to the red–green display for practically all observers at both eccentricities. All observers reported greater viewing comfort for the true-3D display.
Conclusion: Stereo-anomaly is a robust phenomenon. True-3D displays improve depth perception and viewing comfort, most likely because retinal blur provides depth information consistent with disparity.
Application: The true-3D display shows potential for clearly and comfortably displaying objects at different depth planes.

1. Introduction

Stereo-anomaly is the inability to distinguish binocular disparities of different magnitudes and/or signs in the absence of eye movements. About 30% of the population is stereo-anomalous [21]. The stereo-anomaly may present itself at near disparities (often called crossed, meaning that the stimulus is closer than the fixation point), at far disparities (uncrossed), or as an overall lack of depth perception. Specifically, stimuli presented in the defected disparity region are seen at roughly the same depth as monocular stimuli. Subjects who exhibit errors in depth judgments for all disparities (about 3% of the population) are classified as stereo-blind. These findings support the notion that stereopsis is neurally coded in terms of at least three disparity-selective channels: near, far, and tuned [22], but probably there is a continuum of overlapping disparity detectors (see Landers and Cormack [14] for a review). To test for stereo-anomaly short presentation times (<180 ms) are generally used to prevent fixation adjustments. When the stimuli are presented for a longer period of time, many stereo-anomalous subjects have good perception of depth [27,30]. These subjects transform near disparities into far disparities, or vice versa, by making eye movements to alter their fixation in depth.

Stereo-anomaly tests have so far been conducted using simulated depth such as anaglyphic (red–green) stimuli. Red–green stereo diagrams are a convenient and common means for displaying 3D. One image is presented in red, the other in green, directed to the left and right eye, respectively, by means of a pair of red–green glasses. Any desired binocular disparity can be introduced by horizontally shifting the red and green images relative to each other.

However, 3D stimuli that are displayed on a 2D plane like is done by using anaglyphs differ from the real world in several respects [32]. Such a technique manipulates binocular disparity, resulting in vergence of the eyes, but the eyes must maintain accommodation appropriate for the distance of the screen. This forces the observer to decouple the natural coupling of vergence

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and accommodation, and provides him or her with conflicting information about the depth of the stimulus. Besides accommodation, retinal blur provides the observer with depth information that conflicts with depth as indicated by vergence or disparity. Blur is a cue to depth since the amount of blur increases with distance in depth from the eye's fixation point [6,17]. In real-world stimuli, chromatic aberration could in principle be used to determine whether a blurred image is blurred because it is in front of or behind the focal point [19,26]. Several studies suggest that the sense of depth provided by disparity and vergence diminishes if focus cues (accommodation and retinal blur) specify a flat stimulus on a screen [29,4,34]. Another depth cue that usually is not simulated correctly when 3D stimuli are displayed on a 2D plane is motion parallax [23]. In sum, in anaglyphic displays only disparity and vergence argue for a certain depth profile, whereas other depth cues are in conflict with this interpretation. This means that results obtained with anaglyphs may not simply generalize to the real world.

In this paper our prime interest is to investigate whether or not the phenomenon of stereo-anomaly is specific for situations as in the tests performed so far, in which depth is only indicated by disparity while other depth cues provide conflicting information. It could be the case that stereo-anomalous people do not have (major) problems in estimating depth of more real-world stimuli. In order to test this, we asked observers to judge the depth of one or two bars relative to fixation using an anaglyphic display and using a true-3D display. The true-3D display we use here[1] creates a stereo percept by using two (transparent) physical depth planes, providing other depth cues besides binocular disparity. The stimuli were presented for 150 ms which will generally be too short for an effective use of vergence [8] and accommodation [9]. Head movements were minimized by a chin rest, further rendering motion parallax ineffective. Thus, retinal blur was probably the most important extra depth cue in the true-3D display. We presented the stimuli foveally and peripherally. Differences in retinal blur are harder to distinguish in the visual periphery [2,3,15,33], as are differences in depth [20]. We therefore expect a decrease in sensed depth in the periphery as compared to the fovea. In addition, we expect a smaller effect of display type on performance in the periphery than in the fovea as the extra depth cues that are present in the true-3D display are less clear (and thus, less helpful) at larger eccentricities.

Besides the effect of display type on stereo-anomalous people, we are interested in the effect on the general population. To what extent does a true-3D display enhance the quality of depth perception compared to an anaglyphic display? And is a true-3D display more comfortable to view? Previous work suggests that anaglyphic displays are uncomfortable to view due to the conflict between depth cues [32,12] and the relatively long time it takes for the depth percept to build up [11].

Answers to these questions about the quality of depth perception and viewing comfort of true-3D displays are important with respect to the commercial significance of these displays. So far, true-3D displays as used here have received little commercial attention, undoubtedly because the limited number of depth planes makes them unsuitable for the display of 3D pictures and videos. However, for professional applications involving the display of symbolic information, two or three depth planes are quite sufficient to provide a significant operational advantage in terms of parallel rather than serial search patterns [10,11]. We have therefore argued that transparent depth displays are well suited for operator environments like the cockpit. At present we contribute a transparent 3D prototype to the cockpit development within the "Hilas" European Union project (www.hilas.info).

[1] There are other displays available based on different techniques that also provide (close to) correct focal cues (e.g. Perspecta3D, www.actuality-systems.com; DepthCube, www.lightspacetech.com; and displays described in [25,24,1].

In sum, we examined the perceived depth between a fixation mark and two bars for both stereo-anomalous and stereo-normal observers. We manipulated: (1) the amount of depth, (2) the display type (anaglyphic versus true-3D), and (3) the lateral position of the bars (foveal versus 5° peripheral viewing). We hypothesize that perceived depth is larger for the true-3D display than the anaglyphic display and that the true-3D display is more comfortable to view. In addition, we expect perceived depth to be larger and the effect of display to be stronger in the fovea than in the periphery. We will answer the question whether the phenomenon of stereo-anomaly also exists with real depth.

2. Methods

2.1. Apparatus

For both displays, (part of the) stimuli were presented to observers on a single ProLite Iiyama CRT monitor. A chin rest ensured that the viewing distance constantly remained 120 cm. At this distance a pixel subtended an angular dimension of 1.0 by 1.0 min of arc. Refresh rate was 75 Hz. During all conditions the room was darkened.

2.1.1. True-3D display

We constructed a true-3D display by superimposing two depth planes (two monitors) with a half-silvered mirror (see Fig. 1). The fixation square was presented on the fixed CRT monitor. The bar stimuli were presented on the second monitor that could be moved along the rail. We took great care to hide the distance between the mirror and the moveable monitor by darkening the environment, adopting black as background color for the moveable monitor

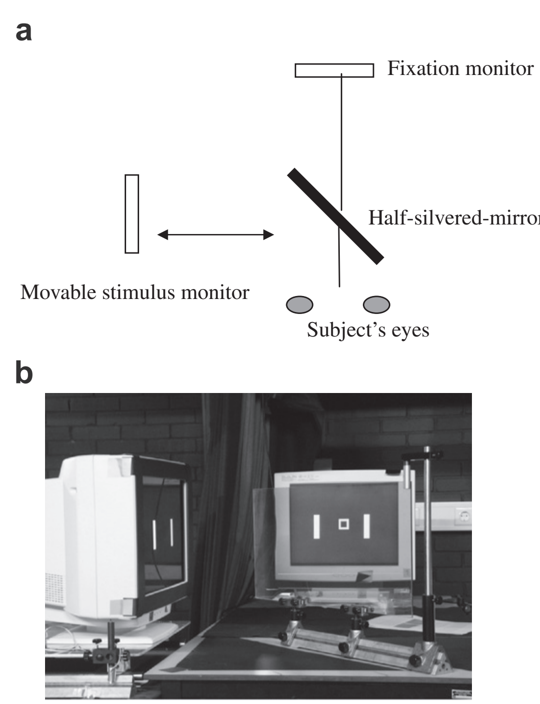

Fig. 1. The true-3D display. (a) Schematic top view. Subjects perceive a combined representation of both displays through the half-silvered mirror. The distance between the 'fixation monitor' and the subject's eyes is fixed at 120 cm. The other monitor can be moved along a rail as indicated by the arrow. The optical distance from this monitor to the subject's eyes varies between 80 and 200 cm. Shifting the position of the movable monitor can create any depth difference. (b) Picture including stimuli (depicted as larger than they actually were for illustration purposes). The stimulus is presented on the monitor on the left, seen as a reflection in the half-silvered mirror. The fixation mark is presented on the right monitor, seen through the half-silvered mirror.

($2.2 * 10^{-3}$ cd/m^2) and dark gray as background color for the fixed distance monitor (0.09 cd/m^2). This luminance difference served to mask the moveable stimulus monitor. The movable monitor frame was covered with black non-reflecting material. In addition the rails were covered with thin soft material to reduce the noise that arose when the monitor was moved. A sampled fragment of the sound that was produced by the monitor when it was moved along the rail was presented through a loudspeaker to mask the remaining noise. Thus, the subject never knew where the stimulus monitor was. Along the rail LEDs were placed to indicate predefined viewing distances to the experimenter. The experimenter manually rolled the monitor in position for each trial.

2.1.2. Anaglyphic display

Subjects viewed the screen through a pair of common red–green filter glasses, mounted on a head rest. This pair of glasses transmit red light to the left eye and green light to the right eye. Two measures were taken to reduce crosstalk below threshold level. The color of the images was adjusted and the hue of a red–green background color was manipulated until cross talk became unnoticeable. The luminance of the background was 0.48 cd/m^2.

2.2. Stimuli

In the foveal viewing condition the stimulus consisted of a single bar. In the peripheral viewing condition the stimulus consisted of one bar 5.0° to the left of the fixation mark and one bar 5.0° to the right. In the foveal condition the single bar has no eccentricity (except for the stereoscopic disparity). A yellow fixation square was presented on the (fixed) screen, subtending 14 min of arc by 14 min of arc, with a line width of 1 min of arc. The vertical bar stimuli were 70 arc min in length and 3 min of arc in width (see Fig. 2). The specified depth of the bars was governed by disparity in the anaglyphic presentation mode, and by monitor distance in the true-3D presentation mode. In the anaglyphic mode, the green stimulus luminance was 0.82 cd/m^2 and the red stimulus luminance was 1.68 cd/m^2. In the true-3D mode the stimulus size in terms of pixels depended on the distance to maintain the same retinal image size. This prevented subjects from using changes in image size as a depth cue. The stimuli were yellow and their luminance on the moveable monitor, seen through the half-silvered mirror, was 9.2 cd/m^2. We simulated eight different distances between the bar(s) and the fixation mark. In the anaglyphic mode, this was achieved by presenting disparities of −1.2°, −0.8°, −0.4°, −0.2°, 0°, 0.3°, 0.6° and 1.5°. These disparities corresponded to stimulus viewing distances in the true-3D presentation mode of respectively 200, 160, 140, 130, 120, 110, 100 and 80 cm, for an inter pupil distance of 65 mm. Thus, the stimuli were presented with either a crossed disparity, an uncrossed disparity, or at the plane of the fixation point (zero disparity).

2.3. Task and procedure

At the beginning of a trial, subjects fixated the small square in the middle of the display. When stable fixation was established, the subject initiated a stimulus presentation by pressing a mouse button. The stimulus was then flashed for 150 ms. This duration was chosen to be sufficiently short to avoid saccades and a vergence eye movement response (for which reaction times are typically larger than 300 ms: [8]. The subject's task was to judge the sign and magnitude of the perceived depth of the bar(s) with respect to the fixation square. Each stimulus presentation was followed by the presentation of a 2D symbolic display, representing the top view of the viewing geometry (Fig. 3). It consisted of a schematic head of the observer and a box. The width of the box was 10°, corresponding to the distance of the vertical bars in the presentations of ±5° eccentricity.

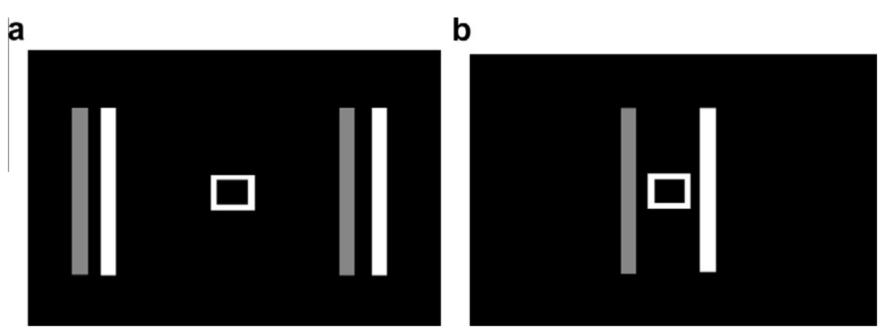

Fig. 2. Examples of stimuli used in (a) the peripheral and (b) the foveal red–green presentation mode. The fixation mark in the form of a square is yellow. In this black and white image the red bar is represented by grey and the green bar is represented by white. The red–green glasses convert the shift in spatial location to the stereoscopic depth percept.

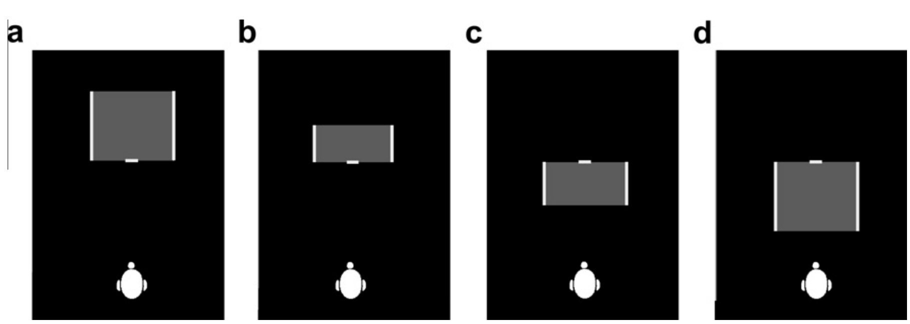

Fig. 3. The schematic representation used by the subjects to score the perceived depth by matching the depth-to-width ratio of the box to the perceived depth-to-width ration of the stimulus bars relative to the fixation symbol. The short horizontal line segment indicates the position of the fixation mark at 120 cm viewing distance. The depth of the box represents the perceived depth, behind (a, b) and in front (c, d). The head represents the observer.

One horizontal line segment represented the position of the monitor screen. Subjects manipulated the vertical position of the other horizontal line segment by moving the computer mouse. The vertical distance between the horizontal lines represented the perceived depth of the stimulus. The subject's task was to make the depth-to-width ratio of the box equal to the perceived depth-to-width ratio of the stimulus. This involves a mental operation that transforms the perceived depth into a top-down view. This method of measuring perceived depth was adapted from van Ee and Anderson [28]. At the end of the experiment, subjects were asked which of the two 3D displays they preferred and why.

2.4. Design

Each subject performed four blocks of trials: anaglyphic foveal, anaglyphic peripheral, true-3D foveal and true-3D peripheral. The block order was counterbalanced between subjects. Each block consisted of four repetitions of stimuli at the eight different depths resulting in 32 trials per block. Within a block, stimulus order was semi-random.

Prior to the experiment subjects were informed about the range of possible perceived depths. Then they performed some practice trials containing the minimum and maximum disparity and three randomly chosen depths, both for the foveal and for the peripheral conditions. The practice trials served to familiarize the subjects with the stimuli and the measurement procedure. No feedback was ever given about the correctness of the responses.

2.5. Subjects

Sixteen subjects participated in this experiment. They were all tested for visual acuity, stereopsis and phoria. Visual acuity was measured using a TNO chart for which subjects had to report the direction of the opening in Landolt C's. Stereopsis was measured with the TNO test for stereoscopic vision [31]. It requires subjects to report the orientation of the 'mouth' of an anaglyphic Pacman-shaped symbol without a time constrain. Note that the observation period for this test is not limited so that subjects are able to make fixational eye movements in depth, meaning that this test does not diagnose stereo-anomaly. Phoria, a latent deviation in the line of sight [5] was measured with a Maddox cross. None of the subjects showed impairments in the visual abilities tested.

Subjects with corrected vision wore their glasses during the experiment. Informed consent was obtained from the subjects after explanation of the nature and the possible consequences of the study. The research followed the tenets of the declaration of Helsinki.

2.6. Analysis

2.6.1. Distinguishing stereo-anomalous from stereo-normal subjects

For determining whom of the subjects were stereo-anomalous and whom stereo-normal, we adopted the procedure as described in van Ee and Richards [30]. For each subject and each of the four conditions we plotted the mean *depth rating* (expressed as the depth-to-width ratio of the boxes as the subjects set them) against the presented disparity. Stereo-normal subjects should correctly perceive stimuli with crossed disparity to lie in front of the fixation point and uncrossed disparity behind.

2.6.2. Dependent variables and statistics

In order to evaluate the extent to which stereo-anomalous and stereo-normal subjects see depth in the different conditions, we look at the *depth range*. This is defined as the average depth setting in the crossed region subtracted by the average depth setting in the uncrossed region, or twice the depth amplitude. We use the *correlation coefficient* between the stimulus depth and the depth setting as a measure of the consistency of the depth percept. The *perceived depth quality* is the depth range multiplied by the correlation so as to capture both of these measures in a single variable.

To test for effects of display type and stimulus location (foveal or peripheral), we performed a repeated measures ANOVA on the depth range with display type and stimulus location as independent variables. We performed independent sample *t*-tests to compare stereo-normals and stereo-anomalous subjects.

3. Results

3.1. Stereo-normal and stereo-anomalous subjects

Four of the sixteen individual subjects showed a pattern typical for stereo-anomaly whereas the other twelve clearly see depth for all presented disparities. Fig. 4 shows the data of the stereo-anomalous subjects. Fig. 5 shows the average data of the 12 stereo-normals. As in van Ee and Richards [30] the depth rating of the stereo-normals reaches a maximum around 1° disparity: the depth range does not continue to increase with increasing disparity. Stereo-normals correctly perceive stimuli with a positive (crossed) disparity to be closer than fixation and stimuli with a negative (uncrossed) disparity to be behind. The four stereo-anomalous subjects share a lack of depth perception but differ in the precise characteristics. Subjects 1 and 2 lack a clear perception of depth for all four conditions. In addition, Subject 2 has a tendency to perceive the stimuli in front of the fixation mark. The data of Subject 3 shows many depth reversals. Subject 4 is borderline stereo-anomalous: the peripheral data are stereo-normal with a low amplitude and foveally he perceives part of the uncrossed disparities as in front (i.e. crossed).

3.2. Effects of stereo-anomaly, display and periphery

Fig. 6 shows the mean depth range for each condition, separately for stereo-anomalous and stereo-normal subjects. Clearly, stereo-anomalous subjects do not only lack a clear depth perception in the anaglyphic displays, but also in true-3D displays. Independent sample *t*-tests show that for all four conditions, depth range is smaller for stereo-anomalous subjects than for stereo-normals (all *p*-values <0.03).

A repeated measures ANOVA on depth range shows a main effect of display type ($F_{(1,15)} = 13.22$, $p < 0.01$) with a larger depth range for the true-3D display than for the anaglyphic display. Thus, the true-3D display in general enhances the depth percept. We cannot say that the stereo-anomalous subjects especially benefit from the true 3-D display because the increase in depth range for the true 3-D display compared to the anaglyphic display is 0.34 for the stereo-normal subjects whereas it is 0.14 for the stereo-anomalous subjects.

The repeated measures ANOVA further shows that there is no effect of stimulus location ($F_{(1,15)} = 2.96$, $p = 0.11$) and no interaction between display and stimulus location ($F_{(1,15)} = 0.09$, $p = 0.77$).

Fig. 7 represents qualitative depth perception for each display and each individual subject. It confirms the finding that stereo-anomalous subjects do not perceive clear depth in both of the displays. It again shows that the quality of depth perception is better for both types of subjects in the 3D display than in the anaglyphic display: practically all data points are below the unity line.

Although our sample of subjects included persons with stereo-anomaly, none of the subjects scored below normal on the stereopsis test as mentioned before. A lack of correlation between the test score and depth range ($R^2 = 0.01$ and $p = 0.72$ for the anaglyphic display, $R^2 = 0.04$ and $p = 0.50$ for the true-3D display) confirms

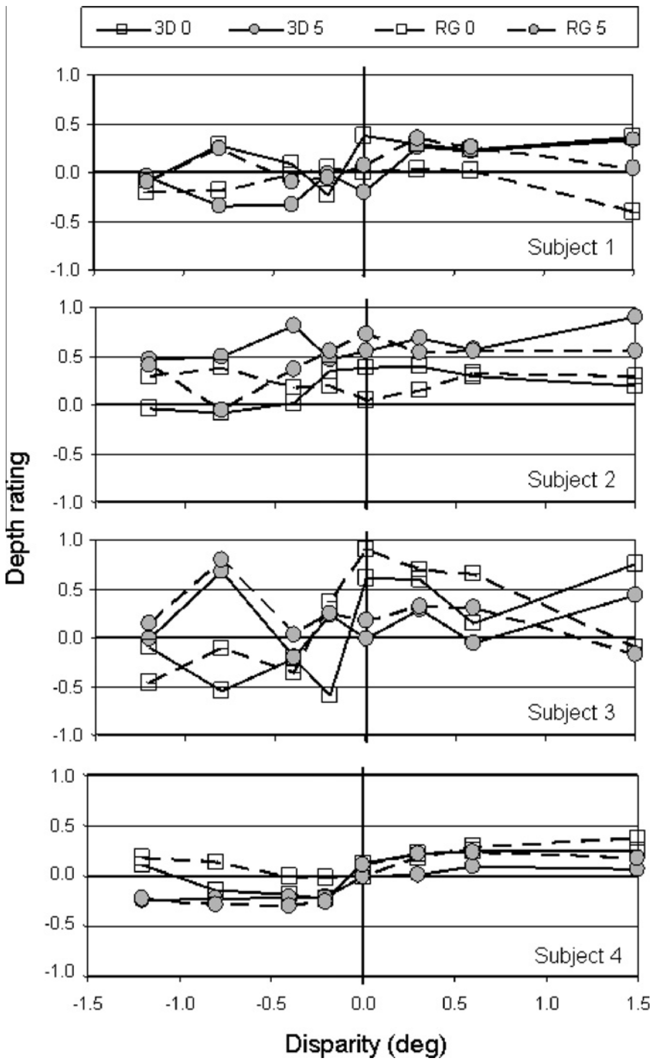

Fig. 4. The average depth rating for each of the four stereo-anomalous subjects and each condition. The solid lines represent the true-3D display conditions, the dashed lines the anaglyphic conditions, the squares represent the foveal and the circles the peripheral conditions. The *Y*-axis represents the perceived depth between stimulus bars and fixation mark. This is expressed as the depth-to-width ratio of the boxes as set by the subjects, so that a value of '1' means that the bars are perceived to be 10 cm in front of the fixation mark. The *X*-axis represents disparity. Stimuli closer than fixation (crossed disparity) are to the right side of this plot (positive sign), whereas stimuli located behind fixation (uncrossed) are on the left side (negative sign).

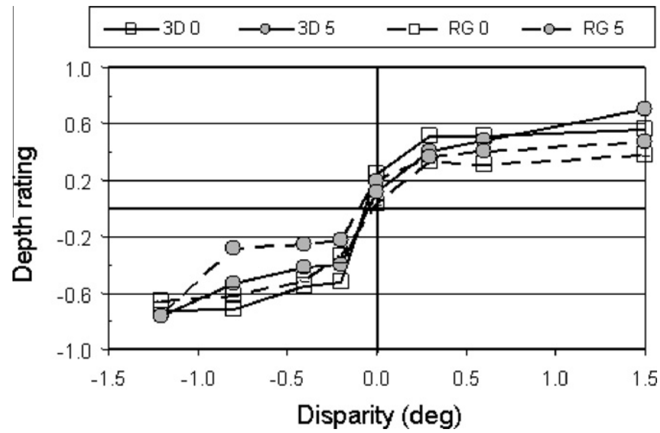

Fig. 5. The average depth rating for the 12 stereo-normal subjects in each condition. Graph conventions as in Fig. 4. Although the magnitudes of the depth settings vary across the stereo-normal subjects, each of them perceived the sign of the disparity correctly.

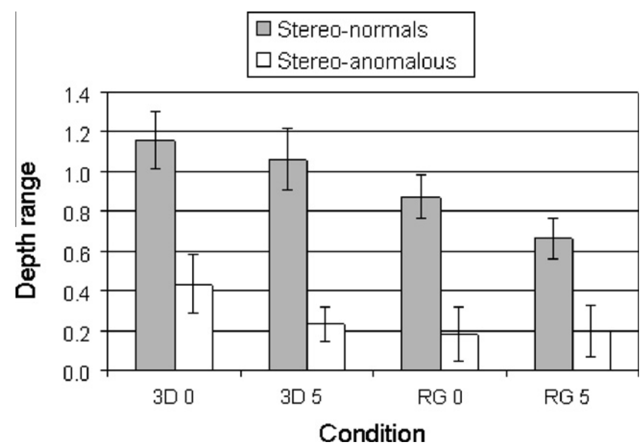

Fig. 6. The average depth range scores for the 12 stereo-normal and the four stereo-anomalous subjects for both display types (3D and anaglyphic) and stimuli locations (foveal and 5° peripheral). The error bars represent the standard error of the mean between subjects.

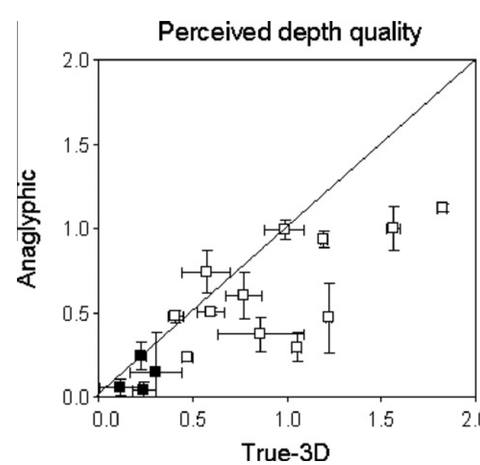

Fig. 7. Quality of the depth percept (depth range * depth correlation) for each individual subject and both display types. Filled symbols represent stereo-anomalous subjects, empty symbols stereo-normal subjects. The diagonal line is the unity line. The error bars represent the standard error of the mean between subjects.

that performance as measured with shortly presented stimuli cannot be predicted from stereovision with unrestricted observation time [30].

3.3. Post-test debriefing

All 16 subjects were more positive about the true-3D display than about the anaglyphic display. They rated depth perception with the true-3D display as more immediate, clearer and more comfortable.

4. Discussion

4.1. Stereo-anomaly

Stereo-anomalous subjects have difficulties detecting the sign and the magnitude of binocular disparity without making eye movements. Here we compared depth judgments for stimuli presented on a true-3D display and on an anaglyphic display to determine whether their low performance also holds for real 3D stimuli. The true-3D display enhances perceived depth for nearly all subjects, yet the four stereo-anomalous subjects still lack a clear depth perception implying that stereo-anomaly is a robust phenomenon. It is not limited to displays that only manipulate binocular disparity while leaving other depth cues unaltered and in conflict with binocular disparity.

4.2. Display effect

As argued in the introduction, retinal blur is the most likely candidate for the improved depth perception with the display containing real depth. In the anaglyphic display, retinal blur indicated no depth difference between the fixation square and the bars. We think that the weighting of this information with the depth information provided by the disparity cue resulted in a smaller amount of perceived depth for the anaglyphic display than for the true-3D display [29,4,34]. Besides the fact that in the true-3D display all depth cues specify the same (non-zero) depth whereas the anaglyphic display does not, there are additional differences between the displays. The red–green glasses used to view the anaglyphic stimuli introduce a luminance difference between the left and right eye, they cause a left–right difference in chromatic aberration, and darken the image. Though we cannot absolutely rule these factors out as to partly causing the different performance between the two displays, a significant contribution seems unlikely. A luminance difference between the two eyes can hamper depth perception by disparity because of latency differences in the processing of dim and bright stimuli. However, this latency difference would be a fraction of our 150 ms presentation time [35]. The effect of the chromatic aberration can at best be indirect, by hampering the accommodation blur cue. Whereas in general increasing luminance supports depth perception [16,18], the effect of display in our study is several orders of magnitude larger than what would have been expected from the differences in luminance [18]. The [3] also predicts only a tiny effect of our luminance difference on the stereoscopic threshold.

4.3. Fovea–periphery

In contrast to what we hypothesized, perceived depth did not significantly decrease in the periphery. Also, we did not observe the interaction between stimulus eccentricity and type of display that we expected, namely a stronger effect of display when stimuli were presented in the fovea than in the periphery. Both of these expectancies stemmed from the fact that discrimination thresholds for blur [2,3,15,33] and stereopsis [20] increase with stimulus eccentricity. Our results show that this does not necessarily mean that the amount of perceived depth diminishes. This form of ‘depth constancy’ is reminiscent of other constancy effects, like contrast constancy [7,13], and is consistent with our daily life experience that the world does not seem to be more flat in the corner of our eyes.

4.4. Viewing comfort

All observers, stereo-anomalous and stereo-normal, rated perceived depth with the true-3D display as more immediate, clearer and more comfortable to view. All of the factors mentioned above are likely to have contributed to the superior viewing comfort [12].

4.5. Commercial significance

The finding that the true-3D display enhances depth perception and viewing comfort makes this kind of display commercially interesting. Perceived depth in true-3D displays could be even clearer when observers are free to move their head so that they can take advantage of instantaneous motion parallax. We have previously argued that true-3D displays are well suited for operator environments like the cockpit [11,10]. Even one extra depth plane can provide a significant operational advantage in terms of search times, especially with cluttered backgrounds.

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