BINOCULAR DEPTH PERCEPTION: DOES HEAD PARALLAX HELP PEOPLE SEE BETTER IN DEPTH?

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ABSTRACT

In this work we study the limits of stereoscopic depth perception on an observer tracking 3D display, which provides head parallax. We perform two experiments where human participants are asked to observe two random dot sinusoidal gratings and choose the less "groovy" one. We use gratings with various amplitude and lateral wavelength, and visualize them with and without head parallax. In each experiment we measure the error rate, decision time and head movements. We present comparative results, which show how these parameters are affected by the presence of head parallax.

Index Terms **—** Head-tracking 3d displays, head parallax, binocular vision, perceptual thresholds, visual quality

1. INTRODUCTION

Most of the so-called *3D displays* are in fact stereoscopic ones – they create the illusion of depth by presenting slightly different images to each eye of the observer. However, such displays generate a scene only as seen from a fixed observation position. The displays, which provide "look-around" effect and allow the observer to see the scene from different perspectives, are known as *full-parallax displays.* Such displays either provide a large amount of views, each one seen from different direction (a.k.a. *multiview displays*) [1] or use observer tracking to update the rendered image each time the observer moves to a different position [2]. In order to ensure sufficient quality, the system driving the display should either store large amount of views or ensure accurate observer tracking and fast rendering. Higher number of supported observation positions produces smoother head parallax, but also introduces higher computational demands.

In this paper, we aim to study the range of observation directions a typical user of a 3D display needs, and also whether full-parallax visualization helps with practical tasks involving depth estimation. There are many studies on the limits of stereoscopic 3D perception, starting with accommodation-convergence rivalry [3] and experiments with random-dot stereograms [4]. Most of them have been done with opto-mechanical setups. More recently, perceptual experiments have been done with stereoscopic displays as well. In [5], the authors use 3D display-based setup to find perceptual limits of disparity perception, and in [6] 2D display is used to estimate the perceptual limits for horizontal motion. Experiments involving sinusoidal depth plane discrimination have been used to study disparity [5] or motion parallax [7] thresholds. In this paper, we aim to follow the experiments in [5], but to use full parallax 3D visualization instead of static stereo 3D setting. We have performed a set of experiments where the observers were presented with a pair of sinusoidal gratings in and had to choose the one with lower depth amplitude.

In the next section we describe the experimental setup – the full-parallax display, the test images and the software used to carry out the experiments. In section 3 we give details about the way the experiments were performed. In section 4 we present the results and in Section 5 we make the conclusions.

2. EXPERIMENTAL SETUP

2.1 Head-tracking display

For our experiments, we used a full-parallax 3D display by zSpace Inc [8]. The display is an integrated solution, which consists of LCD display, fast switching polarization layer, passive polarized glasses, tracking subsystem and a rendering subsystem. The display is a 24-inch LCD with resolution of 1920x1080 and a refresh rate of 120Hz. The switching polarizer can alternate between clockwise and counter-clockwise polarization at 120Hz. In combination with the polarized glasses, this ensures time-sequential stereoscopic image of 60 frames per second for each eye. The passive glasses also contain optical markers, which allow the observer head to be tracked with 6 degrees of freedom with 100Hz. Following the head movement, the system updates the image in real-time, thus providing head parallax to the observer.

The display was used tilted at an angle of 30 degrees, as shown in Figure 1. Regardless of the tilt, the tracking coordinate system is aligned center of gravity, where y increases opposite to the direction of gravity, x increases towards the right edge of the display, and z increases towards the user, parallel to the ground, as marked on the photo in in Figure 1.

Figure 1, The zSpace display and its tracking coordinate system

2.2 Test signals

For our depth discrimination tests we adopted the use of random dot sinusoidal gratings (RDSG). A RDSG is a "groovy" surface, which follows a sinusoidal function in one direction and is constant in the orthogonal direction. In our experiments, we used

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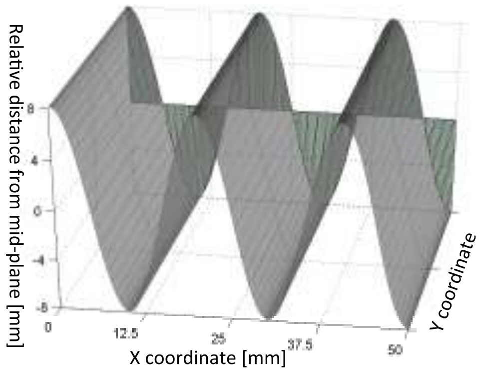
RDGSs which change in x-direction and are constant in z-direction, as shown in Figure 2a. The surface of the RDSG is transparent, and is covered with randomly distributed visible dots RDSG is presented as a full-parallax stereoscopic image. Only two depth cues are present – the disparity of each dot, as it is seen on a different place in each eye; and the parallax of each dot, as it is updated as the observer moves his head around. From a single observation point any RDSG appears as a rectangular area covered with random dots, as can be seen in Figure 2b.



a)

b)

Figure 2, Sinusoidal grating: a) profile of the grating, b) photograph of the display, showing the image intended for the left eye.

The subjects were presented with one pair RDSGs at a time. They were shown side by side, positioned to appear 3cm below the screen surface, and each one had dimensions of 10x20cm. The wavelength (in millimeters) of the sinusoidal function was selected from the following list: 20, 50, 80, 110 and 140. For observation distance of 50cm these wavelengths result in spatial frequencies in the range of 0.08..0.58 cycles-per-degree (CPD). According to [5] the disparity sensitivity in that range does not change much. The amplitude (or, “waviness”) of each pattern was set to one of the following values in millimeters: 8, 4, 2, 1, 0.5, 0.250, 0.125, 0.0625 and 0. We selected this range during the pilot tests, in which amplitudes of 8 and 4 millimeters recognized by all observers. For all wavelengths, the resulting RDSG contains at least one full period. Each RDSG contains 5000 points at a random coordinates. For all wavelengths, there are at least four Voronoi cells per full period across the surface of each RDSG. The oscillation amplitude close to the RDSG edges is linearly decreased (tapered) to zero, so that the sinusoidal profile of the grating does not become visible at extreme observation angles.

2.3 Software framework for subjective tests

We have developed a software framework to help with carrying out the subjective experiments. The framework can be divided into three general stages, namely – input, processing and output – as shown in Figure 3. The input is a list of RDSG parameters, such as horizontal wavelength, vertical wavelength and grating amplitude. Each parameter is expressed as absolute distance in centimeters. Each row in the list describes two RDSGs, which are to be displayed side by side.

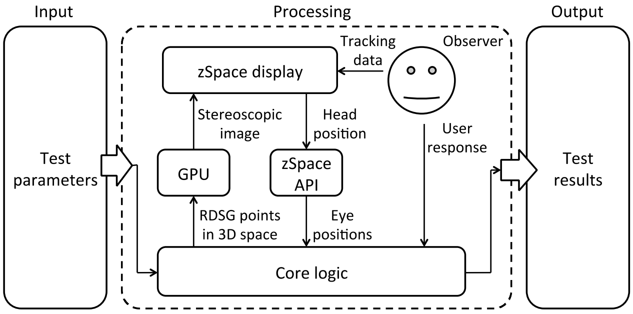


Figure 3, Block diagram of the subjective test framework

The processing block renders the RDSGs using point clouds, sends them to the zSpace screen, and records the user response. It can also record the head position in space with six degrees of freedom, with a rate of up to 100 samples per second. The scene update can be turned off, to simulate stereoscopic display output, or can be turned on to provide head parallax. Two static RDSGs are visualized at a time. On a *keypress* event, the processing block advances to the next row of the input file. The RDSG point clouds are rendered using the openGL’s fix function pipeline, and the driver’s stereo buffer. All points have fixed 2.0 point size, regardless of their apparent depth. In order to avoid flickering artifacts during the scene update, we applied a slight blurring to the rendered points. We used GL_POINT_SMOOTH with GL_NICEST hint, and enabled blending with the GL_SRC_ALPHA, GL_ONE_MINUS_ALPHA function.

The output is stored as a list, where each row contains a time stamp, type of the recorded event, and one or more data values. The system can record the following events: a) a pair of RDSGs shown, and their parameters as data values; b) user key press, with the code of the key as data value; c) head position of the observer, with the x, y, z, yaw, pitch and roll of the head as data values.

3. SUBJECTIVE TESTS

Seventeen participants, aged between 12 and 51 years, took part in the test. All were prescreened for normal stereovision using the Randot stereo test [9]. Each participant took part in two experiments. In the *head-parallax experiment* the observer tracking was used to update the scene on the display, thus providing head parallax to the observer. In the *no-parallax experiment* the updating was turned off, and the display behaved as a regular stereoscopic one. In both cases observer tracking was active, and data about the head movements of the participants was collected at a rate of 10 samples per second. The participants were not told that the display could produce head-parallax images; neither was told if the full-parallax rendering was active. Since our test subjects were not familiar with full-parallax 3D displays, we assume they perceived the visualizations in terms of “natural” or “non-natural” rather that as “having head parallax” or not. We hypothesize that due to the small depth range used in the head-parallax experiment, most observers were not consciously aware of the “look-behind” effect provided by the display.

Each experiment consisted of 140 tests. In each test, the participant was presented with a pair of RDSGs, with the appearance of each pair being similar to the one shown in Figure 2b. In each pair, at least one of the gratings was flat (amplitude equal to zero). The first 5 tests contained all extreme cases, and

were used training sequence. The remaining 135 tests contained all combinations of 9 amplitudes and 5 wavelengths, and each pair was shown 3 times. The order of the gratings in a test and the order of the tests in the sequence were randomized, using different random function for each observer. All tests were performed in a dark room, without any major distractions.
The participants were tasked compare the RDSGs and select an answer which best describes the scene. For each pair, the participant was presented with three choices: a) the left grating is more flat than the right one; b) the right grating is more flat than the left one; c) both are equally flat and/or there is no visible difference.

4. RESULTS

4.1 Error rates with and without head-parallax

We calculated the average error rate (in percent) as a function of the RDSG amplitude. We handled the answers from the *head-parallax* and *no-parallax* experiments separately. In each experiment, the number of correct guesses was averaged across all tests for given RDSG amplitude, regardless of the wavelength or the observer involved. The results, calculated as a percentage of the total amount of tests per experiment can be seen in Figure 4. For RDSG amplitudes smaller than 0.5mm, the average error rate is higher than 50%, regardless of whether head parallax was active or not. For amplitudes larger than 4mm the observers answered correctly 95% of the times. For amplitudes of 0mm (e.g. both RDSGs are flat) most people guessed correctly, as expected. For the amplitude range of 0.5mm to 4mm the presence of head parallax consistently led to a 10% decrease of the error rate. In the *head-parallax* experiment subjects had 50% error rate for 0.5mm amplitude, while in the *no-parallax* experiment the 50% error rate was for 1mm amplitude. This is evidence that head parallax helps with depth discrimination.
We have also found that the average error rates depend on the RDSG wavelength. In general, larger wavelengths produced higher error rate, e.g. they were harder to perceive. As the RDSG amplitude is getting smaller, the error rate for larger wavelength increases faster than the one for shorter wavelengths. For RDSG amplitudes smaller than 0.25mm all error rates are above 90%, regardless of the wavelength. This effect was present both in the *head-parallax* and *no-parallax* experiments, as can be seen in Figure 5.

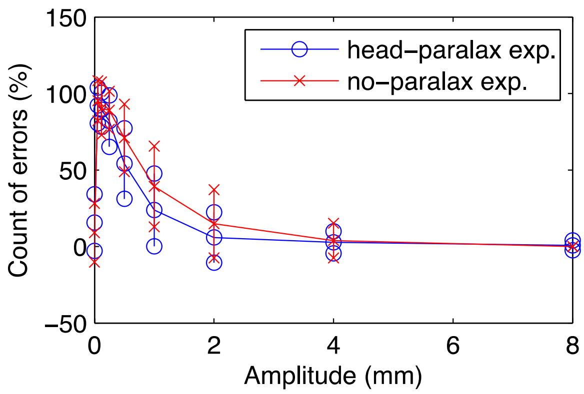


Figure 4, Average error rates per experiment (per amplitude, across subjects and trials), vertical bars represent the standard deviation

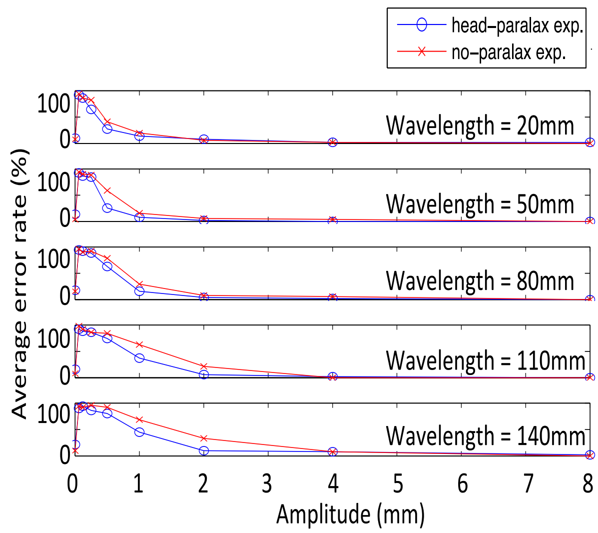


Figure 5, Average error rates (%)for each wavelength (per amplitude, across subjects and trials): a) in the head-parallax experiment, b) in the no-parallax experiment

4.2 Decision time

Using the recorded timestamps, we calculated the decision times in each case. In Figure 6 one can see the average decision time for given RDSG amplitude. For smaller amplitudes the decision time increases, which can be taken as an indicator that the task becomes progressively harder. In the *no-parallax* experiment the decision times were shorter, even though error rates were higher. Our hypothesis for this effect is that observers realize that changing the observation angle does not help with seeing the difference between the RDSGs, and they "give up" trying to do the comparison more easily.

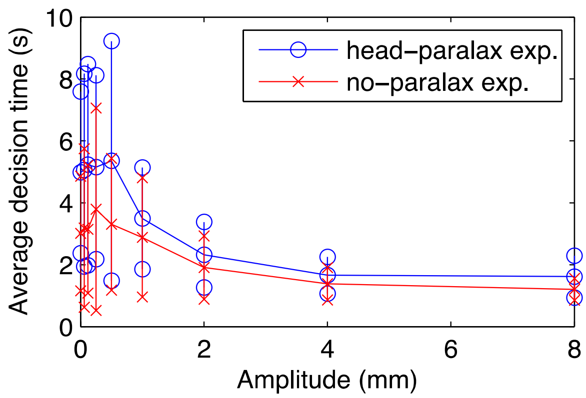


Figure 6, Average decision times per experiment (per amplitude, across subjects and trials), vertical bars represent the standard deviation

4.3 Head movements versus test signal amplitude

We used the head tracking data to calculate the range of the head movements for each experiment. During each test, we obtained a set of head positions in the 3D space. For each test, we calculated the longest distance between two points in the set. We used that distance as an indicator for the range of head movements during the test. In other words, we compared the range of observation positions during different tests. The average movement range per RDSG amplitude is shown in Figure 7. Even though

some observers might have not been aware about the head parallax capabilities of the display, the for smaller RDSG amplitudes they used a wider range of observation directions while assessing the depth. The movement range in the *no-parallax* experiment is consistently lower (~30% less) compared to the *head-parallax*, with less pronounced peak at the lower amplitudes, which can be interpreted as the subjects being aware that head movement does not help with the task if head parallax is absent.

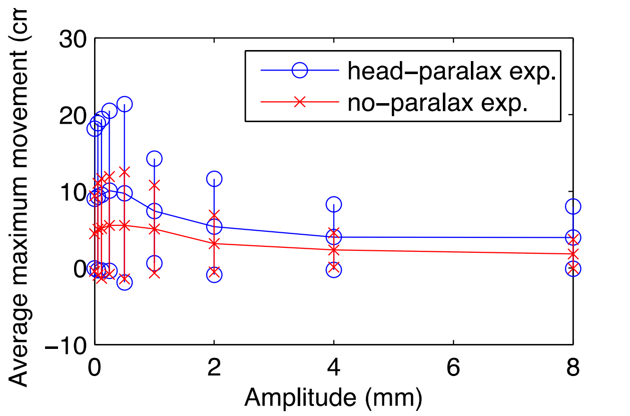


Figure 7, Average head movement ranges per experiment (per amplitude, across subjects and trials), vertical bars represent the standard deviation

4.4 Absolute range of head-movements

The head movement data we collected is describes the head position in the coordinate system of the display, as shown in Figure 1. The center of the coordinate system in in the center of the screen, x increases to the right, y increases opposite of the gravity direction, z increases towards the font of the display, parallel to the ground. In Table 1 one can see the range of head movements for all observers, for each of the six degrees of freedom. We provide the absolute minimum and maximum values, as well as the average ones. This data is indicative for the typical range of observation directions that is used in a desktop setting.

Table 1 - range of head movement

tracked	abs min	mean min	mean max	abs max	unit
x	-38,7	-16,4	13,6	34,8	cm
y	4,4	19,9	34,1	42,1	cm
z	12,3	24,3	54,2	86,6	cm
roll	-7,9	-5,3	-1,5	2,0	°
yaw	-7,5	-2,3	2,2	5,2	°
pitch	-6,9	-3,1	1,8	4,0	°
not tracked	abs min	mean min	mean max	abs max	unit
x	-29,1	-11,8	9,0	21,1	cm
y	13,0	23,2	34,1	38,9	cm
z	9,3	29,4	48,4	76,9	cm
roll	-7,4	-5,3	-1,5	2,3	°
yaw	-3,6	-1,8	2,1	6,9	°
pitch	-6,7	-2,7	1,6	3,9	°

The average range in x direction was approximately 30cm, symmetrically distributed in front of the display. The range in y direction was about 15cm, but we believe that the main reason is the different height of the observers. The typical observation distance was between 25cm and 55cm, which is much shorted than the typical optimal observation distance for an autostereoscopic display [10].

5. CONCLUSIONS

We presented two of subjective experiments involving subjective depth estimation tasks on a stereoscopic, observer tracking head parallax display. We used a set of random dot sinusoidal gratings with varying lateral frequency and amplitude. The subjects had to discriminate between sinusoidal grating and a flat one. In the first experiment the scene was visualized with head parallax, while in the second experiment head parallax was absent. The subjects did not know in advance if head parallax was present. We compared the error rate, decision time, and head movement in both cases.

The results of the experiment show that presence of head parallax results in better ability to discriminate depth. Head parallax also made the task easier – users had more accurate results and needed shorter time to decide. Even if the users are not actively aware of the presence of head parallax, their head movements increased, as the task was getting harder. Additionally, we present the typical range of head movements that occur during both experiments and casual use of the display in a desktop setting.

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