Binocular Depth Perception of Stereoscopic 3D Line Drawings

Yunjin Lee* Ajou University
Yongjin Kim† POSTECH
Henry Kang‡ University of Missouri at St. Louis
Seungyong Lee§ POSTECH

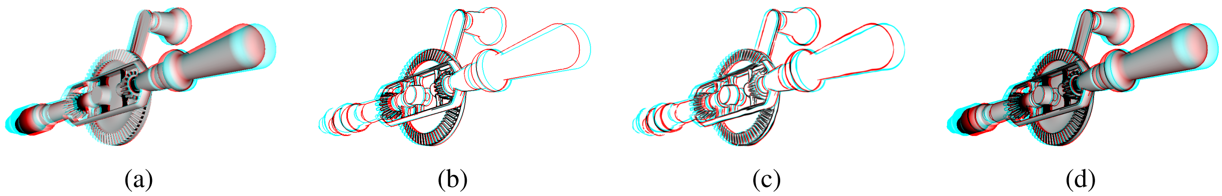


Figure 1: *Depth perception of stereo line drawing. (a) stereo shading, (b) stereo line drawing, (c) stylized stereo lines, (d) stereo shading + stereo line drawing. Our study shows that despite missing interior elements, stereo line drawing often provides enough information to reconstruct depth via binocular fusion. We also find that the style of lines affects depth perception, and that stereo lines themselves can be used as an additional depth cue for normal stereo images. Stereo images in this paper must be viewed through red/cyan anaglyph glasses.*

Abstract

Stereoscopic 3D exploits the effects of stereopsis where the depth perception is triggered by binocular disparity, a difference in image location of an object by the left and right eyes. Despite the dissimilarity of stereo projections in terms of disparity and shape, the human visual system can find the matching stereo pair to fuse using their similarities in terms of color, size, shading, texture, shadows, that are normally present in photorealistic stereo imaging. Now if some of these elements (or depth cues) are missing, such as in non-photorealistic stereo imaging, how will it affect the depth perception and stereo fusion? In this paper, we investigate this issue by conducting a perceptual study on stereoscopic 3D line drawing, in which many of these cues have been abstracted away. We first evaluate the validity of using stereo images composed of lines only, and then compare its performance to stereo images of normal shading. We also examine the effect of changing line style as well as the prospect of using lines as an additional depth cue. Our study shows that stereo line drawing, when compared to stereo shading, does weaken the depth perception but only to a minor degree. On the other hand, modification of line style, and superimposition of stereo lines both have potentials to strengthen the perception of depth.

CR Categories: I.2.10 [Artificial Intelligence]: Vision and Scene Understanding—Perceptual reasoning; I.3.3 [Computer Graphics]: Picture/Image Generation—Display algorithms

Keywords: Stereo perception, line drawing, line stylization

1 Introduction

Stereoscopic 3D (S3D) display technology is becoming commonplace as evidenced by the rapidly growing amount of S3D contents in movies, TV broadcasts, video games, and scientific visualization. In computer graphics, the research on S3D has touched on many issues that arise in generating, enhancing, and manipulating stereo content [Lo et al. 2010; Lang et al. 2010; Didyk et al. 2011; Kim et al. 2011]. While these techniques often deal with photorealistic (natural or synthetic) stereo images, it has been shown that the S3D effect can also be achieved from non-photorealistic (or artistic) stereo renderings [Stavrakis and Gelautz 2004; Northam et al. 2012; Kim et al. 2013b]. This raises an interesting question: How do the *style* and *complexity* of rendering affect the perception of S3D?

Recently, Kim et al. [2013a] developed a stereoscopic 3D viewing system based on *line drawing*, arguably the simplest form of non-photorealistic rendering. A line drawing typically consists of just a small number of lines that represent the salient geometric features of the object, such as creases and contours. Even with such a minimalist representation, the system demonstrated that stereo line drawings are often sufficient to reconstruct depth via binocular fusion. Then again, with lines being the only source of information, some depth cues are clearly missing (e.g., texture, shading, shadows) and we are yet to quantify their influence on the perception (or misperception) of depth in stereoscopy.

In this paper, we conduct a perceptual study on stereoscopic 3D line drawing. We first examine the effectiveness of stereo line drawing in terms of reconstructing depth, particularly when compared to realistically shaded stereo images. We also examine whether the addition of lines to the stereo shading can lead to better depth perception. Another interesting issue in stereo line drawing is whether the style of lines makes a difference in depth perception, which we explore by comparing plain lines vs stylized lines.

2 Related Work

In stereo content production, the focus is often on generating stereo images with proper disparity and coherence between left and right views in an efficient manner. An interesting finding is that one may incorporate certain artistic styles in generating stereo content, and still provide compelling stereoscopic 3D vision. This approach could potentially make the whole stereo experience even more intriguing (Imagine being in an artistic, painted 3D world). This line of work includes stereo painting [Stavrakis and Gelautz 2004; Kim et al. 2013b], stereo edge detection [Stavrakis and Gelautz 2005], stereo abstraction and stylization [Northam et al. 2012], and stereo line drawing [Kim et al. 2013a]. Many of these non-photorealistic

*e-mail:yunjin@ajou.ac.kr
†e-mail:sldk@postech.ac.kr
‡e-mail:kangh@umsl.edu
§e-mail:leesy@postech.ac.kr

stereo renderings offer visually simpler and more abstract looks than their original sources, and yet successfully enable stereoscopic depth perception. Our primary interest in this paper is on how much, if any, degradation in depth perception occurs when such visually abstract stereo images are used. We investigate this issue using a stereoscopic 3D line drawing system [Kim et al. 2013a] based on the premise that the line drawing is by far the simplest, most abstract form of non-photorealistic rendering [Rusinkiewicz et al. 2008], with the minimum possible number of depth cues present.

3 Stereo Line Drawing and Stylization

Computer-generated line drawing of 3D shape generally involves two types of lines to draw: *view-independent* and *view-dependent* (see [Rusinkiewicz et al. 2008] for an extensive survey). View-independent lines, such as creases [Saito and Takahashi 1990], represent the fixed surface features defined by the local surface geometry only, whereas view-dependent lines, such as contours [Koenderink 1984] are formed by dynamically changing features along the viewpoint. Once we identify points on the surface that form these lines, we plot them on the screen to complete line drawing.

In order to generate stereoscopic 3D lines, one could naively draw two sets of lines (one viewed from the left eye and the other from the right) then stereo-fuse them using anaglyph glasses. One problem with the naive approach is that some of the view-dependent lines may not have matching counterparts in the other view, which is not entirely avoidable as it stems from the very nature of view-dependency. Since we rely solely on lines to perform stereo fusion, a line with a missing pair means failure to reconstruct depth in that area. Kim et al. [2013a] resolved this issue by introducing the concept of *stereo-coherency* test for stereo lines. We use this method to generate stimuli for our study on depth perception of stereo line drawings. In our study, we also investigate whether the style of lines has any influence (positive or negative) on the depth perception. Kim et al. [2013a] provides stereo-coherent stylization of lines which preserves coherency of strokes across binocular views.

4 Perceptual Study

Stimuli We generated test stereo images of eight objects and two scenes having various motifs, complexities, object depths, and depth disparities (Fig. 2), via red-cyan stereo rendering at image resolution of 840×525. We implemented the stereo line drawing and stylization method of [Kim et al. 2013a], using OpenGL 3.2 and GLSL 1.5. For stereo shading, we applied Gouraud shading method. The plain (non-stylized) lines were drawn with two-pixel uniform width. For stylizing stereo lines, we used an example brush stroke texture from an artist's painting. For stereo rendering, we set 70cm of distance from the observer to the display and 6cm of interpupillary distance except for the two scenes with many small objects (4cm and 2cm for 'office' and 'living room', respectively) assuming a proportionally small observer.

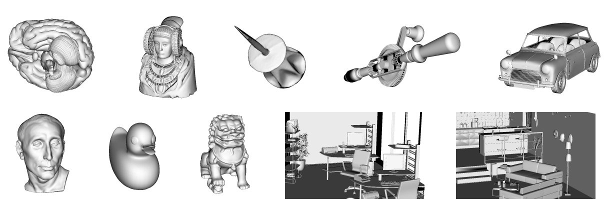


Figure 2: *3D models/scenes used in our perceptual study*

Subjects A total of 31 subjects (14 males and 17 females, from 16 to 33 years old) participated in the experiments. All of them reported normal or corrected-to-normal vision. Before the experiment, we tested stereo vision of the subjects based on random-dot stereogram, and none was excluded due to stereo blindness.

Equipments Each experiment was conducted on a 30-inch LCD display, with a native resolution of 2560×1600. The subjects were seated right in front of and approximately 70cm away from the center of the screen, which is the same distance we used for stereo rendering. Red-cyan anaglyph glasses were given to each subject for observing stereo images.

Tasks In Tests 1 and 2, we use the two-alternatives forced choice (2AFC) without reference [David 1988]. Each test consists of ten *trials* to test with various renderings obtained from different 3D models/scenes. In each trial, two renderings of the same 3D model were presented vertically, one above and one below, on a black background. To minimize bias, we randomized the order of trials as well as the order of vertical placement of images. Tests 3 and 4 similarly present two images vertically for comparison, but the difference is that the subject is allowed to switch the bottom image between multiple selections by clicking an arrow button, to identify the one that best matches the top image in terms of the degree of depth perception. Fig. 3 shows example screen shots of our tests. In each trial, the subject was asked to answer a simple question (by mouse click) prepared for the given test. Each subject took 25 to 40 minutes to complete all the tests.

4.1 Test 1: Monoscopic vs. Stereoscopic lines

In this experiment, we compared monoscopic line drawing vs. stereoscopic line drawing in order to verify that even when the stereo image pair contains lines only, it still successfully generates a stereoscopic 3D effect. In each trial, the subjects were presented with two images on the screen, one monoscopic line drawing and one stereoscopic line drawing. They were instructed to wear anaglyph glasses to observe both images. For each trial, the following question was asked:

- *Q :* Which image gives you stronger stereoscopic 3D depth perception of the model/scene? (Above or Below)

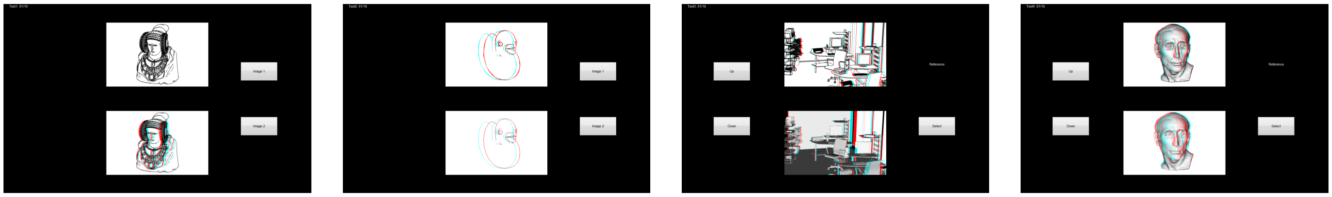
Table 1 (first row) summarizes the test result (100% voted for stereo line drawing) which verifies that stereo line drawing does enable stereoscopic 3D depth perception.

4.2 Test 2: Plain lines vs. Stylized lines

The goal of this test is to investigate whether the style of lines makes a difference in depth perception. In each trial, we showed two stereo line renderings of the same model, one drawn with plain (uniform width) lines, and the other with stylized (non-uniform) lines. The following question was asked for each trial:

- *Q :* Which image gives you stronger stereoscopic 3D depth perception of the model/scene? (Above or Below)

In this experiment, 64.8% of the votes chose stylized lines, while 35.2% chose plain lines (Table 1, second row). For further statistical analysis, we converted votes of each trial to standard z-score z based on Thurstone's Case V [Thurstone 1927; Tsukida and Gupta 2011]. With these z-scores of two methods for 10 images, we performed one-way analysis of variance (ANOVA) and the resulting p-value (= 0.00337) of the data shows that the difference between the two methods is statistically significant at the level of significance $\alpha = 0.05$. In other words, the stylized lines does have the



(a) Test 1 (b) Test 2 (c) Test 3 (d) Test 4

Figure 3: *Example screen shots of the tests in our perceptual study*

effect of achieving stronger depth perception in stereoscopic 3D, although the results may vary depending on the model as well as the subject.

4.3 Test 3: Stereo shading vs. Stereo line drawing

In this test, we evaluated the relative strength of depth perception in stereoscopic 3D line drawing. In particular, we check if the use of line-based stereo images weakens the depth perception compared to the normal, shading-based stereo images. The idea is to prepare a single reference stereo line drawing of a 3D scene that enables depth perception to a certain degree. Also presented is a collection of sample stereo shading images (displayed one at a time) obtained from the same 3D scene but with varying disparities, from which the subject has to pick one with the most similar degree of depth perception to that of the reference line drawing.

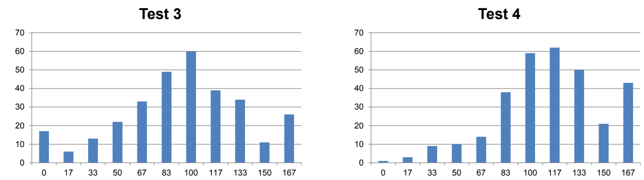
By default, we generate a stereo line drawing using the distance from observer to the display of 70cm, and the interpupillary distance of 6cm. We then generate a series of sample stereo shading images from 11 uniform-sampled interpupillary distances between 0cm (0% of default value) and 10cm (167% of default value) using an interval of 1cm. In case of 'office' and 'living room', the default interpupillary distances of 4cm and 2cm were used, respectively. The maximum scale of interpupillary distance is restricted to 167% to avoid diplopia (double vision caused by excessive disparity).

At each trial, two images are presented vertically on the screen. The top is the reference stereo line drawing generated using the default setting. The bottom is a stereo-shaded image obtained from one of the eleven sample settings described above. If the subject feels that the depth perception from the current sample stereo shading is weaker/stronger than that of the reference image, they must click on the up/down button to check out the next sample stereo shading, and repeat this process until they make a decision. Therefore, the question asked for this test was:

- *Q :* Which stereo-shaded image best matches the reference line drawing in terms of the degree of depth perception? (Select one from the sample stereo shadings)

Table 2 (first row) lists the average and standard deviation of the user selections on this test. Average1 and STD1 are obtained by giving numbers from 0 (0%) to 10 (167%) for the eleven stereo-shaded sample images. Average2 and STD2 are obtained in terms of the percentage of the interpupillary distance for the selected image. The sample image 6 corresponds to 100% of the default interpupillary distance, and the average selection by the subjects is the 5.6^{th} image and 93.49% of the default interpupillary distance. Also, Fig. 4(a) shows that the stereo shading at 100% (default setting) has been selected the most number of times. This means that while the stereo line drawing may weaken depth perception a bit, the difference is minor to many people.

We observe in Fig. 4(a) that sample images 0 and 10 have been selected more than their immediate neighbors. These images are the bookend samples, for which the up/down button stops working in the incoming direction. It is therefore possible that some subjects who have been unable to see much difference between samples may have just stopped the search at either end and clicked the select button from there. In Table 2, Average3, STD3, Average4, and STD4 were obtained after discarding these potential outliers (counts for sample images 0 and 10). Note that while the average pick (5.54 and 92.32%) remains similar, the standard deviation has decreased significantly. We also computed the average per subject of the selected percentages for eleven stereo-shaded images. In terms of the average, the number of subjects who reported less than 100% of depth perception for line drawing was 15 (48.4% of subjects) when counting the bookend samples, and 21 (67.7% of subjects) otherwise.



(a) Test 3 (b) Test 4

Figure 4: *Histograms: the number of user selections (y axis) at each percentage of the default interpupillary distance used for stereo shading (x axis).*

4.4 Test 4: Stereo shading + Stereo line drawing

The purpose of this test is to see if adding lines to the normal stereo rendering has any influence (positive or negative) to depth perception. The test is conducted in the same way as Test 3, except that the reference image now is a stereo shading with stereo lines superimposed on it. The samples are again the eleven stereo shaded images with varying disparities (again from 0% to 167%). We similarly asked the following question for this test:

- *Q :* Which stereo-shaded image best matches the reference image in terms of the degree of depth perception? (Select one from the sample stereo shadings)

Table 2 (second row) summarizes the result of this test. The average pick was 6.79 (113.12% of interpupillary distance) with the bookend samples (0 and 10) included, and 6.29 (104.89% of interpupillary distance) without. Also, in terms of the average selected percentage for eleven stereo-shaded images, the number of subjects who reported increased depth perception with lines present was 24 (77.4% of subjects) with the bookend samples included, and 21 (67.7% of subjects) without. This tells us that adding lines to the stereo shading does have the effect of strengthening the depth perception.

Test	Choices	Question	Choice 1	Choice 2	p-val
1	mono lines (1) vs stereo lines (2)	more depth perception?	0 (0%)	310 (100%)	–
2	plain lines (1) vs stylized lines (2)	more depth perception?	109 (35.2%)	201 (64.8%)	0.00337

Table 1: *Summary of Tests 1 & 2. Each row shows the number and percentage of votes for the given test.*

Test	Reference	Choices	All choices				Excluding 0 & 10th choices			
			Average1	STD1	Average2	STD2	Average3	STD3	Average4	STD4
3	stereo lines	11 stereo shadings	5.61	2.53	93.49%	42.25	5.54	1.89	92.32%	31.51
4	stereo lines + stereo shading	11 stereo shadings	6.79	2.11	113.12%	35.24	6.29	1.77	104.89%	29.46

Table 2: *Summary of Tests 3 & 4. Each row shows the average and standard deviation of selections for the given test.*

5 Discussion and Future Work

Our study shows the validity, usefulness, strengths and weaknesses of line-based stereoscopic 3D imaging. In the absence of color, shading, texture, and shadows, all the subjects still managed to stereo-fuse the two line drawings and reconstruct depths. While the degree of depth perception does get diminished somewhat, it is still comparable to that of photorealistic stereo imaging (about 90% performance on average). As an example implication of this, some low-budget, cartoon-style 3D movies or animations can be similarly effective to the viewers at least in terms of generating the S3D effects.

The style of lines does make a difference towards better depth perception, which may have something to do with the fact that stylization of lines often adds clarity and reduce confusion in the drawings [Goodwin et al. 2007]. On the other hand, there are a wide variety of existing line styles many of which we have not tried. It would make an interesting future research topic to find the optimal line style that maximizes the stereo perception of depth, and also see if there are styles that diminish it.

One of our tests also shows that the stereo lines can be used as an additional depth cue for enhancing depth perception. This could possibly create an interesting trade-off between visual realism vs. depth perception. If we superimpose lines over photorealistic stereo images, the viewers might feel that they are in a less-than-realistic 3D environment and yet the 3D depths may be felt more strongly (e.g., might be useful in video games).

Another possible future research direction is to extend this study to 'animated' stereo line drawings, in which the issues of temporal coherence, motion parallax, and visual comfort may have to be addressed as well.

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