Relative Importance of Depth Cues on Portable Autostereoscopic Display

Maija Mikkola
Department of Signal Processing
Tampere University of Technology
Tampere, Finland
maija.mikkola@tut.fi

Atanas Boev
Department of Signal Processing
Tampere University of Technology
Tampere, Finland
atanas.boev@tut.fi

Atanas Gotchev
Department of Signal Processing
Tampere University of Technology
Tampere, Finland
atanas.gotchev@tut.fi

ABSTRACT

Depth of a three-dimensional scene is perceived using several different visual cues. The process of perceiving depth is delicate and vulnerable to artefacts. On autostereoscopic displays the aim is to enhance the sensation of reality of the experience by the added three-dimensionality without the need for aiding glasses. The factors that contribute to achieving a plausible 3D effect on autostereoscopic displays are numerous: for example stereoscopy combined with a supporting set of monocular cues: perspective lines, shadows, and textures.

The goal of this study is two-fold. First, to gather knowledge on how different characteristics of a 3D scene impact the correct estimation of depth. Second, how the same characteristics impact on perceived quality. These were studied using subjective tests. The studied characteristics were chosen to be five different depth cues — three monocular and two binocular cues. The chosen monocular cues were shadows, texture and focal depth. For binocular cues, two different stereoscopic disparities were used: one optimal for a portable 3D display, and another designed for a HD resolution and later scaled down for a portable device making the disparity decrease. In addition, combination of all aforementioned cues was examined. All of the cues were also studied with three different compression levels (no compression, 90% JPEG compression, and 50% JPEG compression).

A quantitative study using a portable autostereoscopic display in controlled laboratory environment was conducted. The results of this study indicate that the stereoscopic depth cues outperform the monocular depth cues in accuracy and speed of estimating depth in a 3D video. Interestingly enough, these results are not consistent with the ratings of perceived quality and acceptance. Furthermore, compressing images seems to have a significant effect on the accuracy and speed of depth estimation, and also on the perceived quality.

Keywords

Depth cues, autostereoscopic display, 3D experience

1. INTRODUCTION

In real-life situations, three-dimensional (3D) effect is created by a combination of different visual depth cues. In 3D videos the depth effect is created by binocular parallax, but other cues contribute to the sensation of depth, too. The advantage of 3D videos over 2D ones is expected to be in the enhanced naturalness of the displayed content by increment of the depth effect and the so acquired feeling of "being there" [1, 2, 3]. In order to make the overall 3D experience satisfying for the spectator a 3D scene must meet some requirements. For example, the spectator's capability of estimating depth correctly in the 3D scenes is very important.

In order to meet the viewer's expectations it should be well thought what the most important components of a plausible 3D are and whether the presence or absence of certain depth cues affect the correct estimation of depth.

Not only produced quality but also perceived quality can have a strong impact on the task of depth estimation [4]. The overall user experience (UX) is a complex and subjective phenomenon and has many definitions. Most of them stress the interaction between the user and the product, and the context in which the product is used [5, 6].

This paper is organized as follows. First, background on the topic is given. In Section 2 binocular and monocular cues to depth are presented. In Section 3 a short introduction to portable autostereoscopic displays is given. In Section 5, the used research method is presented. The method of analysis and the experimental results are presented in Section 5, and the results are discussed in Section 6.

2. DEPTH CUES

The HVS uses several methods in defining the distance of objects on the scene. Depth cues can be divided into *binocular depth cues* that require both the eyes, and *monocular depth cues* that can also be seen with a single eye. Studies with *random-dot stereograms* have shown that the binocular and monocular depth cues are independently perceived [7]. The depth range used by human is quite narrow but highly accurate [8].

2.1 Binocular Depth Cues

Human eyes are separated from each other on average by approximately 6.3 cm [9]. This separation causes two different depth cues: *vergence* and *stereopsis*. Because of their nature, these depth cues are called binocular cues to depth. Vergence is a depth cue given by the angle between the two eyes when they are fixated to an object. The horizontal separation causes the two retinae to capture slightly different images. This is called *binocular disparity* and produces stereopsis [7, 10].

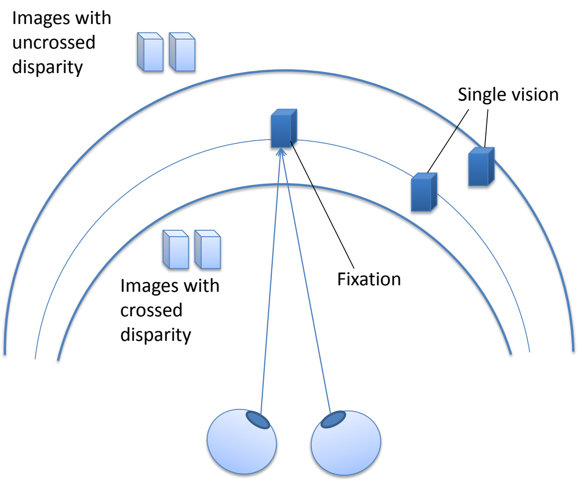

Figure 1: Panum's fusional area. The objects within the area are seen as single images. The objects further away are seen with uncrossed disparity, and the objects closer to the viewer with crossed disparity.

The area of depth of focus is illustrated with the concept of Panum's area — it is the area where a point on one retina will fuse with a single point on the other retina, as illustrated in Figure 1. The points further away cannot be fused and produce double images with uncrossed disparity. The points closer to the viewer produce double images with crossed disparity [9].

Accommodation and vergence work in concerted action, because usually the objects which are in focus are also fixated upon. Crossed retinal disparities cause convergence movements, and uncrossed disparities cause divergence [11]. When eyes converge to an object, they often also accommodate to bring the object to focus. On a stereoscopic display this might introduce problems since they eyes converge on an object but the lens accommodation stays on the screen where the image is sharpest [9, 12]. This phenomenon is called *accommodation-vergence rivalry*.

2.2 Monocular Depth Cues

At longer distances, the binocular cues have less importance and pictorial cues such as shadows, perspective lines, textures, size, and colours are more important. Failure to present credible pictorial cues might cause effects such as puppet theatre effect or cardboard effect [13] and thus destroy the sensation of depth.

Occlusion and motion parallax are strong relational depth cues both for short and long distances [14, 15, 16, 17]. Texture in sufficiently symmetrical or constant patterns is a good cue to depth. Shadows work as a depth cue by indicating the size, shape, orientation and parallax of different objects. Like parallax, occlusion, and texture, shadows are also a relational depth cue. The functioning of scale as a cue to depth relies on the fact that the sizes of familiar objects are known. Focal depth has been proposed to be an extensive cue to depth that is effective on different distances [18]. Accommodation functions by changing the optical power of the lens in order to focus on an object. This mechanism works as a depth cue especially for short distances for which two eyes cannot see the object. Accommodation and focal convergence are tied together — one usually gives raise to the other.

The importance of depth cues on perceiving depth is a linear combination of the cues, weighted by the apparent reliability of each cue in that particular scene [19, 20, 21]. The weight given for each cue can be affected also by previous experiences. In the findings of Johnston et al. [20], when the distance increases the weight of the texture increases. They speculate that this might be because of the decreasing importance of stereopsis on longer distances.

3. PORTABLE AUTOSTEREOSCOPIC DISPLAYS

Stereoscopic displays are expected to enhance the feeling of presence by immersing the viewer more vividly in the displayed space [3]. Autostereoscopic displays go even further in creating such a sensation — they provide the 3D effect without any aiding glasses or other extra devices. However, the stereoscopic or autostereoscopic displays cannot still give a perfect representation of the 3D world.

In autostereoscopic displays each eye is provided with a distinct view. Unlike with the stereoscopic displays, the view separation structure is fused straight on the display, and no user-worn devices are needed.

The two main types of technologies for view separation are called *parallax barrier* and *lenticular sheet*. The parallax barrier method works by restricting the light through the pixels to certain output angles using arrays of optical apertures. The lenticular sheet method has a light refracting layer comprised of columns of micro-lenses fused on the display, and light rays through different pixels are refracted in certain directions. Other types include for example holographic and volumetric methods [22, 23]. The binocular displays can be further divided into two categories: ones with a fixed viewing zone and ones where an active eye tracker is used [24].

Multiview autostereoscopic displays provide several spots where the 3D effect can be perceived. This is done by refracting (lenticular sheet) or blocking (parallax barrier) light from certain subpixels to different directions. This lowers the brightness of the image, and for a portable device, further increases the problem of the insufficiency of the power supply. On the other hand, mobile devices are normally used by one user at a time, a fact that favours the use of two-view displays.

4. RESEARCH METHOD

The study was divided into two parts, to a subjective depth estimation performance analysis and to a subjective quality evaluation. In the first part, a subjective study was done to collect information on if the participants perceived the depth correctly or not. In the second part, the perceived quality was rated on an unlabelled scale and the acceptance on a binary scale.

In this study, *Absolute Category Rating* (ACR) method was used, i.e. each item is shown one at a time and rated independently [25]. Participants' ratings can drift over time, and can be affected by the context — for example by the order in which the stimuli are shown[26]. To compensate for this problem, images were shown in random order and several times.

4.1 Test Stimuli

Test stimuli were rendered with a ray-tracing program POV-Ray, and rendering was controlled by a script created with Perl.

Test images were designed to consist of a constant background scene and a number of objects. Objects on the scene were decided to be balls with number labels. Their locations and sizes were randomized in order to avoid hints suggested by the constant locations and sizes of the objects. Only one of the numbered objects could be on the same depth with the reference object, and there was a fixed range that was kept clear from other objects.

Six different depth cues were used: focal blur, shadows, texture, binocular view optimal for the 3.1" device the tests were run with, binocular view optimal for a large HD display, and a combination of the first four aforementioned cues. These cues were used in images with three different JPEG compression levels: best quality with no compression, good quality with some slightly visible compression artefacts (90% JPEG compression), and low quality with noticeable blockiness (50% JPEG compression).

4.2 Participants

A total of 30 participants were recruited. The participants were aged between 20-33, mean being 25 years. 68% of the participants were males and 32% females. All the participants were classified as "early adopters" or "early mainstream", as defined in the Domain Specific Innovativeness Scale [15].

The participants were required to have normal or corrected to normal visual acuity and color perception. For screening of vision, *hyperopia* was tested with a Snellen Chart [27]. Color vision was tested using Ishihara test [28]. Stereo vision was tested using Randot Stereo Test ($\leq$ 60 arcsec).

4.3 Test Procedure

The test was conducted in a laboratory in the Institute for Media Technology at Technische Universität in Ilmenau, Germany. Test room illumination was fixed before starting the test. Test conditions for viewing were adapted for mobile viewing based on the recommendations recommendations of ITU-R BT-500 [25].

The device that was used in this study is a prototype of an autostereoscopic display created by NEC LCD Technologies with a Horizontal Double-Density Pixel (HDDP) arrangement [29]. Size of the display is 3.1" with resolution of 427×240 pixels. It is backwards compatible with 2D content and has the same resolution in 2D and 3D modes.

The participants were given a short oral introduction to the test procedure, and shown a training set to get familiarized with the test material, viewing images on autostereoscopic display, and to find the optimal viewing distance. The training set consisted of 12 images, chosen from the test material so that it represented it extensively.

In both the parts of the experiment, the participants were shown similar images, where only the used depth cues and compression levels varied.

In the depth estimation test, the participants were asked to evaluate which of the numbered objects in the test images were at the same distance with the reference object. This was done in order to find out if some depth cues dominate in terms of importance. The answer was given by pressing a corresponding number on a numeric keypad. The given answer and the answer time were recorded.

As another way of measuring the importance of different independent variable pairs, speed of carrying out each depth estimation task was recorded. This was expected to give a straightforward hint of the easiness of conducting each task, and thus stating which combinations made the depth easy to estimate.

A quality evaluation study was conducted, aiming to gather information about the participants' satisfaction in each image by asking their assessment about the quality acceptance and overall quality according to their opinions on an unlabelled scale from 0 to 10. The acceptance of quality was given on a binary scale by selecting "Yes" or "No" [30].

5. SUBJECTIVE EXPERIMENTS

In both the parts of this study the presumptions for normality were not met (Kolmogorov-Smirnov $>$ .05) and non-parametric methods were chosen. The significance level chosen for this study was $p<.05$. *Friedman's test* can be used for data with non-normal distribution to measure differences between several, and Wilcoxon test two data sets [31].

McNemar's test can be used for comparisons between data sets with nominal data [31]. To study the correlation, a Spearman's test for non-parametric data was used [32].

Chi-Square test of independence can be used to study the independence of the distributions of two nominal data sets, and McNemar's test to analyze nominal data to test differences between two categories in related data [31].

In order to lower the risk of making the Type I Error with multiple comparisons, Bonferroni correction was used. The used significance levels were $p<.0167$ for different compression levels and $p<.0033$ for different depth cues.

5.1 Simulator Sickness Questionnaire

Binocular viewing is vulnerable to artefacts and an unnatural stereo scene might cause physical side effects such as headache or nausea [33]. To find out if the 3D images caused these side effects, a simulator sickness survey was done using a Simulator Sickness Questionnaire (SSQ) [34, 35]. The test was used as a relative measurement tool to eliminate the impact of possible symptoms the participants might have had prior to the test. The SSQ was filled out by the participants before the experiment and straight after the test. To study how the possible symptoms change in function of time, the test was repeated every four minutes until 12 minutes had passed since ending the experiment.

Right after the test, increased disorientation and oculomotor related symptoms were reported. When 12 minutes had passed, the participants' physical state had already returned to the initial level.

The new, strange viewing experience might give some explanation for the experiences of disorientation. However, the oculomotor symptoms can as well be explained by the nature of the experiment as the task required the participants' full concentration.

5.2 Speed of Depth Estimation

A Friedman test indicates a significant difference between the times used on depth estimation task on three different compression levels (X^2 = 10.117, p<.0167).

A Wilcoxon test indicates a faster conduction of depth estimation when the image is not compressed at all compared with the lower quality images. The difference between the best and good quality is significant (Z=-2.644, p<.0167), and between the best and the low quality images even more remarkable (Z=-3.815, p<.0167).

A Friedman's test for different depth cues indicates that there is a significant difference between the variations of the data sets (X^2=140.871, p<.05). The results of a pairwise Wilcoxon indicate that for the images with stereoscopic depth cues the recorded times are faster than for the images with only monocular cues. See Figure 2 for illustration. The significance level was p<.0033.

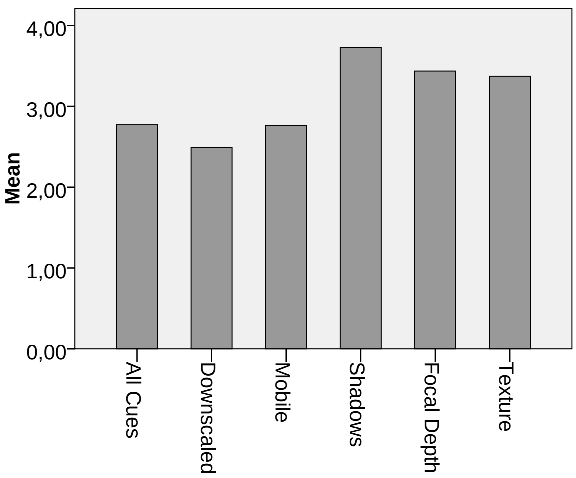

Figure 2: The means of the times used for images with different depth cues. The depth cues from left to right are All Cues, Downscaled, Mobile, Shadows, Focal Depth, and Texture.

5.3 Correctness of Depth Estimation

A McNemar test indicates that there is a difference between the correctness of ratings in the low and the good quality images (X^2=23.223, p<.0.0167), as well as between the low and the best quality images (X^2=23.770, p<.0167).

When testing the differences between the correctness of ratings on different depth cues, a McNemar test indicates that the images with stereoscopic cues gave more accurate results than the images with only monoscopic depth cues. See Figure 3 for illustration. The significance level in use was p<.0033.

Spearman's test indicates that the times used for estimating the depth and the correctness of the result have a negative correlation (r=-.148, p<.01).

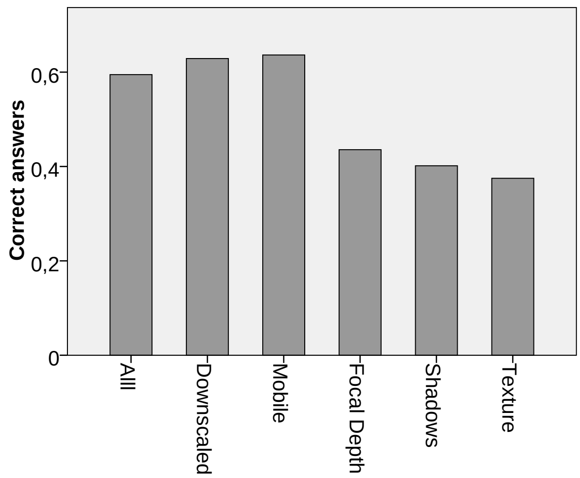

Figure 3: The correctness of results of the depth estimation task for images with different depth cues. The bars represent (from left to right) All Cues, Downscaled, Mobile, Focal Depth, Shadows, and Texture.

5.4 Quality Ratings

A Friedman's test indicates a significant effect for the quality ratings given on different levels of compression (X^2= 403.5, p<.05). A Wilcoxon signed rank test indicates a significant preference of the images with lower compression. The Best quality was preferred over Low quality (Z=-16.456, p<.0167), and over Good quality (Z=-10.082, p<.0167). Good quality was preferred over Low quality (Z=-12.287, p<.0167).

A Friedman's test for the quality ratings given for images with different depth cues indicates that some data sets differ from each other significantly (X^2 = 420.944, p<.05). A Wilcoxon signed rank test indicates that the images with depth cue Downscaled were rated with highest scores, and followed by Mobile and Shadows. The two latter ones had no significant difference between them. Then, the images with textured objects were preferred over the ones with focal depth and the combination of all cues.

5.5 Acceptance Ratings

A Spearman's rank test indicates a correlation between the qualities and the acceptance values (r=.707, p<0.01). To find the threshold for acceptance ratings, a method by Jumisko-Pyykkö et al. [30] was used. The threshold was searched by connecting the binary satisfaction data with the quality ratings. The threshold was determined based on the statistics of the acceptable (Mean: 7.66, SD: 1.77), and the unacceptable quality ratings (Mean: 4.0, SD: 1.68). The threshold value was defined to be around 5.8.

A Chi-Square test of independence showed a significant effect on acceptance data between the data sets. A McNemar test between the cases showed that for all the three different compression levels, the effect was significant. The low quality images are in the category of unacceptable (Mean: 5.03, SD: 2.079).

For the acceptance of different depth cues, the McNemar test indicates that the downscaled images got the best ac-

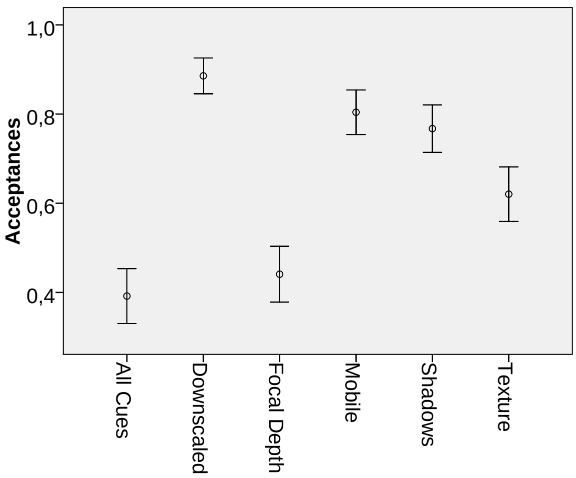

Figure 4: Acceptance ratings for the six different depth cues. The used cues from left to right are as follows: a combination of all cues, downscaled stereoscopic image, an image with focal depth, a stereoscopic image designed for a mobile display, shadows, and texture.

ceptance ratings. The ratings given for the images with shadows and images designed for a portable display are only little lower than the ones given for downscaled images. The images with texture were only barely acceptable. The images with "All Cues" and "Focal Depth" as depth cues are regarded as unacceptable (Figure 4). Based on this study, it cannot be determined whether the combination of all cues got low ratings because of the strong influence of the focal depth.

6. RESULTS

According to previous studies, motion parallax and stereopsis are considered the most important depth cues [36, 37]. These theories are in line with the results of this study — **all the images with stereoscopic depth cues got significantly better ratings than the images with monocular cues when measuring the accuracy and speed of depth perception**. The finding that additional cues to depth (shadows, texture, focal depth) did not lead to better results might be an implication of the supremacy of stereopsis over monocular depth cues on portable displays.

In particular, focal depth seems to get a low ranking in all the tested areas: in accuracy, efficiency and in acceptance, which is a result that was found surprising, and a question for further studies. In informal discussions after the experiments, several participants complained that the images with focal blur appeared out of focus. If the blur was considered to be mainly an error, it might also affect its reliability as a depth cue.

The compression level had a significant effect on both the accuracy and the speed of depth perception. The binocular HVS is very vulnerable to lose the depth effect if artefacts are presented. The results of this study indicate that the quality of the image has a significant effect on the correctness of depth estimation, but an even greater effect on the speed of estimation. The quality might have some imperfections and the depth might be still perceived perfectly, but as the quality drops further, so does the accuracy of depth perception.

The time used for estimating the depth and the correctness of the estimation had a negative correlation, indicating that if **the depth estimation was conducted fast, the result was also most likely correct**.

The sizes of the objects in each image were randomized and thus the participants were forced to judge the depth using other depth cues. A rapid evaluation of the images and the corresponding answers implies that even though the participants did not have any reason to assume the object sizes to be constant, the size might have been taken as a depth cue from time to time. If one of the cues, for example texture, was considered not to be reliable enough, the judgement might have been based on a stronger cue — size. This is supported by the theories presented by Young, Johnston and Knill, stating that the importance of depth cues can be seen as a weighted combination of the presented cues, based on their reliability in each situation [19, 20, 21].

Not all combinations of different depth cues were studied. The images exhibited either a single type of a depth cue or all the cues simultaneously. It could be further studied whether the focal blur is really considered an error or if it actually contributes for the depth estimation in HVS. Additionally, an interesting topic for further studies would be how much strong perspective lines, texture, or size facilitate the depth estimation task.

Interestingly, **the effectiveness and accuracy of the depth estimation was not consistent with the results of the quality evaluation studies**. A previous study by Strohmeier et al. [38] indicates that the depth effect only contributes to the quality perception when there is little compression. This kind of effect can be easily understood, especially in case of 3D video: if lower quality affects the efficiency of depth perception, the binocular HVS might not have enough time to create a plausible 3D effect for moving objects. On low bit rates, the benefits gained by added depth might be invalidated by the artefacts. This gives further support to the assumption that 3D perception is an extremely delicate mechanism and vulnerable to artefacts.

7. CONCLUSIONS

In this study, the influence of different depth cues and compression rates on the perceived quality and depth were examined. The results indicate that on portable autostereoscopic displays, the stereoscopic depth cues outperform the monocular ones in efficiency and accuracy.

Compression artefacts seem to have a significant impact on depth perception — especially on the speed of observing the depth effect. Even slight blockiness can deteriorate the efficiency of perceiving a depth effect, and this is problematic in 3D videos.

It should be noted that the three-dimensionality brings notable additional value compared to 2D in terms of UX, but requires better quality. Attention must be paid to error resiliency in all the video processing phases from content creation to display. Especially, if high motion scenes have any artefacts, the depth effect can be easily lost. The study has further underlined the findings that the binocular HVS is extremely vulnerable to artefacts.

Further studies should be done in order to understand more explicitly if some monocular depth cues can give additional aid in depth perception when combined with stereopsis.

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