

The Effect of Out-of-focus Blur on Visual Discomfort When Using Stereo Displays

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Figure 1: Images with and without simulated out-of-focus blur. On the left a virtual scene is shown, on the right a photographed one.

ABSTRACT

Visual discomfort is a major problem for head-mounted displays and other stereo displays. One effect that is known to reduce visual comfort is double vision, which can occur due to high disparities. Previous studies suggest that adding artificial out-of-focus blur increases the fusional limits, where the left and right image can be fused without double vision. We investigate the effect of adding artificial out-of-focus blur on visual discomfort using two different setups. One uses a stereo monitor and an eye tracker to change the depth of focus based on the gaze of the user. The other one uses a video-see through head mounted display. A study involving 18 subjects showed that the viewing comfort when using blur is significantly higher in both setups for virtual scenes. However we can not confirm without doubt that the higher viewing comfort is only related to an increase of the fusional limits, as many subjects reported that double vision did not occur during the experiment. Results for additional photographed images that have been shown to the subjects were less significant. A first prototype of an AR system extracting a depth map from stereo images and adding artificial out-of-focus blur is presented.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Artificial, augmented, and virtual realities—;

1 INTRODUCTION

It is crucial for stereo AR systems to offer good stereoscopic vision that does not lead to simulator sickness, minimizes visual discomfort and at the same time offers a realistic perception of depth. This is an issue not yet solved completely. Especially for video-see through (VST) head mounted displays (HMD) it is difficult to achieve stereo vision without visual discomfort and realistic depth perception, as many parameters like position, orientation and field of view (FOV) of cameras and monitors have to be chosen correctly. Many effects related to stereo vision in HMDs have been studied in

the past. So the vergence-accommodation conflict which is considered to be a major source of visual discomfort has been studied extensively [16]. Min and Jense [12] studied the effect of angle and distance between the cameras and the FOV of cameras. Livingston et al. [9] investigated the influence of contrast and disparity on the accuracy of stereo perception. Kooi and Toet [6] estimated threshold values for a wide range of causes for viewing discomfort in stereo images.

Beneath other effects like the vergence-accommodation conflict, high disparities are another cause for visual discomfort in stereo vision [16, 7]. As an effect of the separation s between both eyes or cameras, objects are seen at different positions in the left and the right eye as illustrated in figure 2. On the left hand side, the case for normal vision is illustrated and on the right hand side when using a stereo display. Both eyes will always converge towards the object that is currently fixated such that this object is projected to the fovea, which is the part of the eye where sharp vision is possible. Objects that lie at a different depth as the fixated point will be projected to different locations in the left and the right eye. Let p_{focus} be the point that is focused and p_{near} be the point in the image that is closest to the eyes. The disparity can be measured as angle, $d_a = \alpha - \beta$. When using a HMD let $p_{focus,l}$ be the position where the point p_{focus} is shown on the display and the other points be defined the same way. Here the disparity can also be defined as distance on the display $d_i = (p_{focus,l} - p_{focus,r}) - (p_{near,l} - p_{near,r})$. The disparity for the far point is defined analogous. On the one hand this effect helps to perceive depth, on the other hand a high disparity leads to visual discomfort and high disparities reduce the capability of fusing both images to one. The maximum angular disparity where images can be fused has been estimated as being only 0.1° in the fovea and 0.66° in the peripheral visual field [7].

The negative effect of high disparities on the ability to fuse images is not only a problem of stereo displays but also for the human vision. In the real world this effect is only perceived in extreme cases e.g. when focusing on a far object while putting a finger close to the eye a double image of the finger will be seen. The occurrence of double vision is called diplopia. It might surprise that disparity is considered as a problem when using stereo displays, as this effect does not really pose a problem for real vision.

The human eye always focuses on a certain distance. As the

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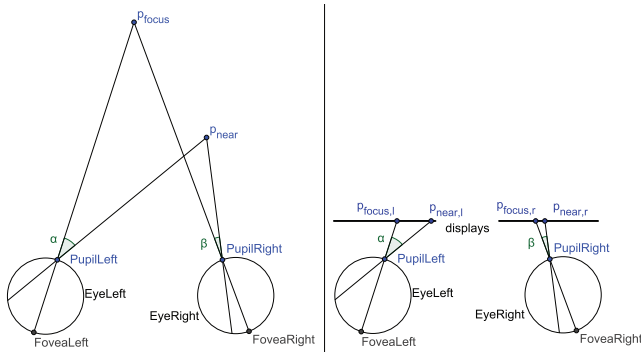


Figure 2: On the left the effect of disparity in normal vision is illustrated and on the right when using a HMD.

pupil has a certain diameter, objects that are at a different distance as the fixated point are blurred and therefore areas where disparities occur are blurred. This can again be seen when focusing on a far object while putting the finger close to the eye. Double vision of the finger is perceived but the finger will be blurred. We believe that on stereo displays the effect of double vision is more problematic as in most AR or VR systems only very low amounts of out-of-focus blur are present. AR systems use mainly small cameras with small sensors and small aperture widths which both leads to a large depth of field. For virtual objects, blur is usually missing completely as rendering is in most cases done with camera models that do not produce out-of-focus blur.

Several papers have investigated this or related effects. For stereo monitors, Nagata [13] performed an experiment where a foreground object was shown in front of a background consisting of random black and white boxes. One version where the background was blurred and one where the background was sharp have been presented to three test subjects. It was shown that blurring the background increases the limits of binocular disparity where the two images could be fused. Blohm et al. [1] investigated on a stereo monitor the effect of adding different amounts of artificial blur to stereo images and video sequences. The test subjects were asked to look either on the foreground while the background was blurred or vice versa. Pairs of images with different amounts of blur were presented to the subject. The experiment showed that higher amounts of blur are preferred. The effect of adding synthetic depth of field to motion sequences was also investigated by Sun and Holliman[20]. A scene with a flying spaceship was shown, where the fixation point was always on the spaceship and the foreground and background were blurred. In this study, subjects preferred the non blurred version. It was assumed that the depth of the scene, and therefore the disparities, were not large enough to create diplopia and therefore the effect of adding blur did not improve the perceived quality. Another reason could be that the test subjects were not explicitly asked to always focus at the spaceship. So it is possible that subjects focused at parts of the image that were blurred. In a survey on visual discomfort, Lambooi et al.[7] suggested to build a system that uses an eye tracker to estimate the focus point of the subject and add artificial out-of-focus blur based on this. However they did not implement such a system.

In order to reduce visual discomfort we plan to build an AR system that uses an eye tracker to estimate the 2D gaze position of the user on the display. Using a method to recover a depth map of the images it is possible to obtain the 3D gaze position. Knowing the 3D focus point and using the depth map, artificial out-of-focus blur can be added to the images. In this paper four contributions on using out-of-focus blur to reduce visual discomfort are presented. First, we present the first implementation and evaluation of a system

that uses an eye tracker to estimate the focus point, adds artificial blur to non fixated layers, and presents the image using a stereo monitor, as suggested by Lambooi et al. [7]. Second, we perform the first evaluation on the effect of out-of-focus blur on a stereo HMD. Third, we present a first prototype of an AR system that recovers depth information from the stereo cameras of a VST-HMD and uses this information to add out-of-focus blur. Fourth, the first experiments not only using virtual images, but also photographed scenes are presented.

2 RELATED WORK

Several other methods to address the problem of diplopia are known in computer graphics. A comparison of different methods can be found in [21]. These methods either involve a static or dynamic change in the separation of the virtual cameras or some sort of image or view scaling to reduce the amount of disparity. For most AR applications these methods are not well suited, because they either change the camera separation which will lead to a wrong perception of depth, or they change the FOV which is known to have negative effects on stereo vision [12]. Using another FOV as the one of the HMD would also lead to a magnification or demagnification of the image, which is usually not desired in AR.

For AR, artificial blur has been applied to virtual objects in order to better merge them with camera images. Fischer et al. [4] added artificial motion blur and synthetic noise to virtual objects such that they look more similar to real objects recorded by cameras. An advanced camera model that includes motion blur, distortions and effects from the image processing pipeline of a camera has been shown by Klein and Murray [5]. However, they did not model out-of-focus blur. Okumura et al. [14] tracked a marker and estimated out-of-focus blur and motion blur from the appearance of the marker in the image. Virtual objects close to the marker are blurred based on the estimated blurring of the marker. Using this method a better integration of virtual objects into the camera image can be achieved, but it is not possible to change the focus distance or apply artificial blur to real objects in the camera image. A template matching-based tracking that can handle motion blur has been presented by Park et al. [15] and has been used to add artificial motion blur to virtual objects.

The effect of out-of-focus blur as depth cue has been studied in [11] by showing images that only consist of noise, where some parts are blurred. Their study showed that blur is only a minor depth cue. The use of blur as a way to reduce visual discomfort has not been considered in their work.

3 METHODS

3.1 Objective and Hypothesis

The objective of this study is to investigate the effect of out-of-focus blur on visual discomfort when using stereo displays. We performed experiments both for a HMD and a stereo monitor. The main hypothesis is, that applying blur to non-fixated layers in a scene will lead to lower visual discomfort. We also assume that the effect will be stronger in images with higher disparities.

3.2 Subjects

A total of 18 subjects participated in the test, where one subject only performed the experiment using the stereo monitor. Four were female and 14 were male and the average age is 25.44(±3.13). The participation of all subjects was voluntary and they have not been compensated. One subject did not pass the stereo vision test that was performed at the beginning and the results from this subject were removed. For four people the eye tracker did not work precise enough when using the monitor. For these people the focus distance was set manually as done when using the HMD.

3.3 Apparatus and stimuli

We used two different setups, one with a stereo monitor and one with a VST-HMD. The first setup consists of a stereo monitor using polarized glasses. Additionally we used an eye tracker device, which in most cases worked without problems when wearing the polarized glasses. Instead of showing images from video cameras we have chosen to use a virtual scene which gives us full control over all parameters, like separation and angle of the cameras, FOV and position of all objects. The monitor is a 22" Zalman ZM-M220W monitor with a resolution of 1680x1050. It is a horizontal interlaced stereo display using polarization which halves the resolution per eye. The subject was positioned at a distance of 80cm in front of the screen, resulting in a horizontal field of view of 32°. Behind the subject a black fabric was placed to avoid reflection on the monitor, which is very glossy. A Tobii X60 eye tracker was used to estimate the gaze point of the user. The virtual scene was rendered for both eyes using quadbuffering. Knowing the 2D gaze position on the monitor, the 3D gaze point in the virtual scene can be obtained by reading out one pixel in the depth buffer.

In previous work on reducing visual discomfort due to high disparities, different methods have been used. Nagata [13] did not aim at generating out-of-focus blur but only investigated the general effect of sharp or blurred background. They used a low-pass filter to generate the blurred images. A filtering approach that is based on a geometric optical model has been used by Blohm et al.[1] to blur video sequences. While this method provides good results, it is too slow for real-time processing. An accumulation buffer method, where the image is rendered multiple times always moving the camera slightly was used by Sun and Holliman[20]. We first tried this method but did not use it for the experiments, because performance for more complex scenes is low and this method only works on purely virtual scenes. Other methods for adding synthetic depth of field are discussed in [3]. We have chosen to use a reverse-mapped z-buffer method. The implementation we used is similar to the one described in [17]. It is implemented on the graphics processing unit (GPU) and uses two subsequent rendering passes. In the first rendering pass the scene is drawn without blur and at the same time for every pixel the blurriness is computed based on the distance to the gaze point in z-direction, where the z-axis points into the screen. This is done by reading the depth from the depth buffer and comparing it to the depth of the gaze point. The blurriness for every pixel is stored in an additional texture. In the second pass each pixel is blurred by sampling neighboring pixels using stochastic jittering. The distance of the sampled points is scaled by the blurriness of the pixel and every sampled point is weighted by the blurriness of that point. The sampling of the points is done in the world coordinate system and not in image coordinates. As an effect of this a point that is closer to the viewer will be blurred with a higher radius, as it is the case in reality. The depth of each point is also considered to avoid that background objects blur into foreground objects.

Eleven different virtual scenes were shown to each subject. In every scene, the foreground object was at a distance of 80cm and the distance of the background image varied between 102cm and 294cm resulting in on-screen disparities between 3% and 10% of the screen width. Scenes with different contrast and different foreground and background images have been used. Some of the images are photographs some consist only of a texture. In addition to the virtual scenes we also used real, static scenes where two images with a baseline of ~7cm have been taken using a photo camera. The photos always contain one foreground object and one or several background objects where the distance to all background objects is very similar. The photos have been segmented manually into foreground and background. Using the same setup as above, the foreground and background can be blurred based on the gaze of the user. An example of a virtual and a real scene can be seen in figure 1.

The second setup consists of a nVisor SX OST-HMD with a res-

olution of 1280x1024 and a horizontal field of view of 48°. While eye trackers that can be integrated into HMDs are commercially available (e.g. by Applied Science Laboratories) we do currently not have such a device. Therefore the focus distance in this setup is set manually. For visualization, this setup uses the same virtual scenes, respectively the same photographic images as above. Also the blurring is performed using the same technique.

3.4 Procedure

For the test method we followed the ITU-R BT.500-11 recommendation [2] for subjective assessment of the quality of television pictures. Two previous studies on the effect of blur on visual discomfort followed the same recommendations [20, 1]. For assessment of stereoscopic images, the simultaneous double stimulus for continuous evaluation method is recommended by the ITU and was used in our experiment. First all subjects had to undergo a stereo vision test to see if they can perceive stereo images. For this, a random-dot-stereogram was used. Next it was decided randomly to start either with the stereo monitor or the HMD. For the monitor a calibration of the eye tracking system was performed. Afterwards one scene was shown to illustrate the two different visualization methods. Next, eleven virtual scenes were shown to the subject. Every scene was presented in a version with blur and one without blur. Whether first the blurred or the non blurred version were shown was randomized for every image. In alternating manner, the subject was asked to look at the foreground and the background, for four seconds each. This was repeated twice, then a mid-gray level screen was shown for five seconds and the same scene was shown again using the other visualization mode. After having seen both modes the subject could either choose to rate their quality or to see both sequences again. To rate the images the subject was asked to put one mark for each version on a vertical continuous scale, that is divided into five equal lengths, corresponding to the ITU-R five-point quality scale. The five parts on the scale correspond to quality ratings ranging from bad to excellent, but the subjects were free to put their mark at any place of the scale. Afterwards the mark of the subject was measured and the results are converted to a scale between 0 and 100. The first three of the eleven scenes were only used to stabilize the result and were not used for the evaluation. The eight scenes that were used for the statistics are always the same scenes. After the virtual scenes were shown, the three photographed scenes were presented to the subject. The order in which the images were shown was randomized for every subject. After finishing the experiment on the HMD and the monitor the subjects had to fill out a short questionnaire on how often they use different kinds stereo displays and whether they wear glasses.

4 RESULTS AND DISCUSSION

For every subject we averaged the scores for all eight virtual, respectively all three real scenes. The results of all subjects were screened for outliers based on the ITU recommendation but no one had to be eliminated. The quality ratings have been tested for normal distribution using the Kolmogorov-Smirnov test and they can be considered as having normal distribution. A paired one-tailed t-test was performed on the average ratings. The results are shown in table 1 and the distribution is shown in figure 3. For both, the monitor and the HMD, the difference is significant at a level of $p < 0.05$. However, the difference between the blurred and non-blurred version is lower as we expected. We realized that, after having finished with the first few subjects. We started to do interviews with some of the subjects after they finished the experiment. In the interviews many people reported that they did not perceive double vision at all, even for the images that have high disparities. With some subjects we performed a threshold test, where we showed a virtual scene consisting of a foreground and background object. At the beginning the camera separation was set to 0. We step wise increased the cam-

	no blur	blur	p-value
HMD virt.	63.56(\pm 12.15)	71.55(\pm 9.15)	p=0.008
HMD real	71.15(\pm 16.77)	73.47 (\pm 17.06)	p=0.359
Monitor virt.	62.04(\pm 11.35)	70.21(\pm 10.42)	p=0.026
Monitor real	70.35(\pm 19.82)	79.02 (\pm 12.97)	p=0.079

Table 1: Means, standard deviations and p-values of the quality ratings. P-values that can be considered as significant are drawn bold.

era separation and asked the subject to report any inconvenience or double vision to us. Some subjects reported double vision very soon while others did not perceive double vision even with on-screen disparities above 30% of the screen width. We noticed that people perceiving double vision very soon, did prefer the blurred version. For the subjects that did not perceive double vision, the results were not that clear. However, as we only performed the threshold test for few subjects, we could not obtain any significant results for that. Some subjects reported that they did not experience any discomfort and they rated the image quality based on other criteria. So some people liked that they are not distracted from the foreground when the background is blurred. Others liked it more to see the whole image sharply.

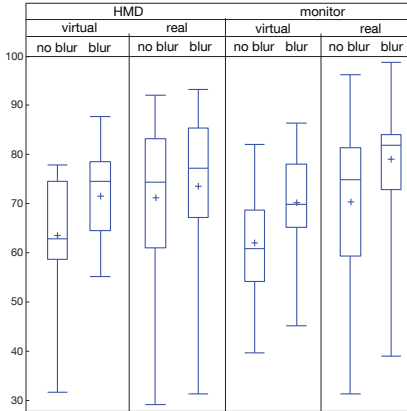


Figure 3: Boxplot of the mean quality ratings per subject, showing median, upper and lower quartiles and the mean values (cross).

We assumed that the blurred version would be preferred especially in scenes with high disparities. The average rating for every single image is shown in figure 4, where the disparity increases from left to right. As can be seen in figure 4 this assumption could not be confirmed. We believe that there are two reasons why this assumption did not hold true. First, as discussed above, many people did not perceive double vision in the first place. Second, additional effects like the contrast of the images seem to affect the perceived quality very much. So the image with 6% disparity is the image with the highest contrast. This image got the lowest quality rating of all images while most subjects did clearly prefer the blurred version. There have been two previous studies where it was shown that subjects preferred artificial depth of field [1] respectively blurring the background [13]. In both studies, images with very high contrast were used.

In another study, where no significant difference between using artificial DOF or not could be shown [20], low contrast images have been used. These results suggest that the use of artificial DOF would be preferred especially in high contrast images, which can be confirmed by our results.

There is no significant difference between using the stereo monitor and the HMD. The difference for the real images is not as big as

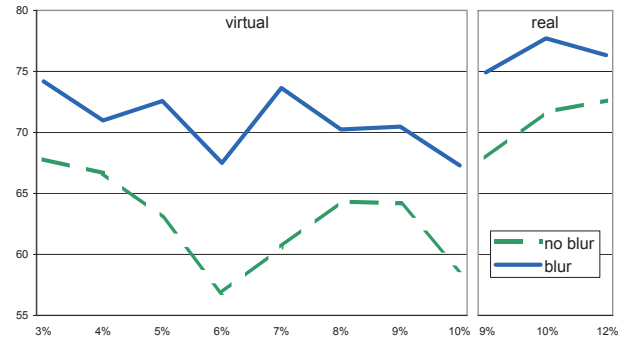


Figure 4: The x-axis shows the disparity in percent of the screen width. On the y-axis the quality rating is shown. The values are averages from both, the monitor and the HMD.

for the virtual scenes as can be seen in table 1. While there is a difference between the mean quality ratings, this difference can not be considered as significant. The ratings are less consistent and have a higher standard deviation compared to the virtual scenes. While for the virtual scenes many subjects did only experience smaller differences between the two versions, for the real scenes more people had a strong preference towards the blurred or non blurred version. So we can assume that additional effects that are present in the real but not in the virtual images influence the results. But it must also be noted that none of the photographs had strong contrast.

We made some additional interesting observations. Three subjects said that they prefer a sharp foreground with a blurred background over a completely sharp scene, but they prefer the completely sharp scene over a sharp background and a blurred foreground. Sun and Holliman [20] reported the same comment by two subjects in a study on depth of field in animated stereo scenes. Some subjects mentioned that they did not like the transition when the focus distance changes and two people assumed that the effect of adding depth of field would be more beneficial in moving scenes.

5 PROTOTYPE OF AN AR SYSTEM USING ADAPTIVE BLUR

There are several ways how such a system could be built for AR. To do this, three issues have to be addressed. First, the gaze of the user has to be tracked. This can either be done using eye tracking which is already commercially available for OST-HMDs or simply by assuming the gaze point to be in the center of the image. Second, the depth of the gaze point has to be known. In a stereo HMD this information can be obtained from a stereo depth reconstruction. Another solution would be to use a time-of-flight (TOF) camera and project the depth obtained from the TOF camera to the images of the video cameras. The third problem is to blur the image. This can be done using a camera with small depth of field and a focus that can be controlled from a computer. Another solution could be to use coded aperture cameras [8] that can both recover the depth information and change the focus after the image has been obtained. However, all methods that use real out-of-focus blur generated by the lens and the sensor, have the problem that in AR usually small cameras with small lenses are used, which only produce a low amount of blur. Therefore the use of artificial blur is to be preferred, which requires a depth map of the scene. See [3] for an overview of different methods to simulate depth of field.

To avoid the use of additional hardware we have decided to estimate the depth by a stereo depth reconstruction using the two cameras of the HMD. In order to compute the depth of a pixel, the disparity of the pixel between the left and the right image has to be computed by a disparity matching. Prior to the disparity matching the two camera images of the HMD have to be rectified as described by Loop et al. [10]. Our current disparity matching solution is im-

plemented in OpenCL in order to be executed on the GPU. For efficient execution we utilize shared memory as well as GL/CL sharing. The matching algorithm is based on local normalized cross-correlation (LNCC) with 9x9 windows. For correct matching, even within homogeneous regions, we use a Gaussian pyramid based approach like Mikhail et al. [18] with four to five levels. In the current version we only classify pixels into fore- or background. For this purpose we decided to calculate the disparity for all but the highest level. This ensures a strong performance boost, as by now the blurring and the disparity calculation are done on the same GPU. Both components on their own are able to achieve nearly real-time. Due to this, further implementations will be based on two GPUs for separate calculation.

In our current version the users sees the camera images only on a monitor not on the HMD itself. The gaze is tracked and the parts of the image that are at a different depth as the focus point are blurred, using the same methods as described before. Adding virtual objects and also blurring them is straightforward and requires only setting the reconstructed depth map as depth buffer before drawing an object. Our current prototype is promising, but the quality of the depth reconstruction and the speed have to be further improved to build a reliable system.

6 CONCLUSION

We performed an experiment on using artificial depth of field to reduce visual discomfort when using stereo displays. Our main hypothesis was that out-of-focus blur would reduce visual discomfort due to double vision. Results showed a significantly better perceived quality when using out-of-focus blur in virtual scenes. However, for photographed scenes results were not significant. Taking into account that many subjects reported that they did not perceive double vision at all we could not confirm our initial hypothesis without doubt. Looking at the results and from interviews we did with some of the subjects, we assume that there is a multitude of reasons why some subjects like or dislike the use of blur. Especially for the photographed scenes the results are not very consistent among the subjects.

So, when building an AR system the use of artificial out-of-focus blur should be considered, but it should not be assumed that all users prefer blur. As mentioned before, several subjects preferred only blurring the background when looking at the foreground, but not the other way round. So it might be a good solution build a system that only blurs the background when the user looks at nearby objects. We must further investigate the interplay between different aspects of the image. So the contrast seems to influence the perceived image quality strongly. Also the influence of further characteristics of the images like color, homogeneity or repetitiveness should be investigated in more detail. Future studies should take into account differences between the subjects. We investigated only whether wearing glasses or working regularly with stereo displays affects the perception of visual discomfort due to disparities and we did not find any significant relation. Other parameters that could influence the perception are long vision, short vision or ocular dominance of one eye. While in our study only static scenes with fixed viewpoint have been shown, it has to be investigated whether the same assumptions hold true for dynamic scenes. Next steps for building a working system using a HMD will be an improvement of the depth reconstruction algorithm or the additional use of TOF cameras, as the results are currently not reliable enough.

Especially, when combining artificial depth of field with other methods to improve stereo vision in AR, as for example virtual convergence [19] or simulation of camera artifacts [5], we have to further investigate the different effects that lead to comfortable stereo vision. Insight on how to do this could also be gained from other areas where stereo vision is important. So, in stereo photography, which is already done for over hundred years, many rules of thumb

exist. So e.g. the maximum on screen disparity for stereo photography is usually considered to be 3%. Another area that is currently very active are stereo movies, that make extensive use of blur and other methods to reduce visual discomfort.

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