Illusion of Depth in Spatial Augmented Reality

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ABSTRACT

Spatial augmented reality (SAR) is an emerging paradigm that differs from its origin, the traditional augmented reality (AR), in many regards. While traditional AR is a well-studied field of research, the characteristic features of SAR and their implications on the perception of spatial augmented environments have not been analyzed so far. In this paper, we present one of the first studies, which investigates the perceived spatial relationships between a user and their SAR environment. The results indicate that perceived depth of real-world objects can be manipulated by projecting illusions, such as color or blur effects, onto their surfaces. For the purpose of evaluating and comparing the illusions of interest, we developed a prototypic setup for conducting perceptual SAR experiments. Since this testing environment differs significantly from its counterparts in virtual and augmented reality, we also discuss potential challenges, which arise from the nature of SAR experiments.

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

1 INTRODUCTION

In the last few years, an extensive amount of research has been done in the area of augmented reality (AR), along with the development of several see-through head-mounted displays, such as the Microsoft Hololens, and handheld devices. Although traditional AR systems imply a strong feeling of presence inherently, they are still limited in their capability to provide a realistic impression of spatial relationships between virtual and real-world objects as different studies showed in the past [7, 17]. In the emerging paradigm of spatial augmented reality (SAR), sometimes also referred to as 3D projection mapping, this issue is addressed by separating the display from the users. Instead of superimposing computer-generated virtual information on top of a view of the real world, the virtual content is projected directly onto real-world objects and, therefore, the objects' appearance can be changed in a variety of ways. For instance, SAR can be used to simulate different materials of a single object (e. g., [21]) or to transform a whole room into an interactive display (e. g., [14, 15])[1]. While most previous projects used SAR to augment physical objects with additional information, the focus of this paper is to investigate whether perceived spatial relationships between real-world objects and the user can be manipulated by projecting onto these objects.

In order to alter a person's perception, the stimuli in their environment can be manipulated using SAR. For this purpose, we employ techniques which are inspired by the way how humans process image or video material. For instance, different color temperatures

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[1]For more examples visit http://projection-mapping.org/.

and luminance values are used in traditional arts to create apparent depth in 2D paintings [4] and the adjustment of the disparity range of video streams is best practice in the film industry to improve the viewing experience in 3D movies [18]. Based on these approaches, we differentiate between monoscopic pictorial illusions, including the manipulation of color, luminance and sharpness in the image space, and stereoscopic illusions, which utilize the binocular vision of humans. In order to evaluate the effects of these illusions, we developed a prototypic setup for SAR experiments which will be discussed in the following sections.

In this paper, we contribute to the body of basic research on perceptual psychology in SAR and we present first approaches to leverage perceptual illusion techniques, which may find applications in real-world SAR scenarios. For instance, distance and size misperception in real-world scenes may be addressed by depth changing illusions that are introduced with SAR techniques, thus compensating for overestimation or underestimation. Moreover, such techniques may prove useful in guiding the attention of observers in the real world to certain objects using subtle pre-attentive manipulations.

The remainder of this paper is structured as follows. Section 2 provides background information regarding the field of perceptual illusions in SAR. In Section 3 we introduce our prototypic setup, which is used for a preliminary study that is discussed in Section 4. Section 5 concludes the paper and discusses future research directions in this field.

2 BACKGROUND

Visual artists make use of a variety of techniques to induce a sensation of depth in their 2D paintings (for a review see [11]). Due to the fact that even flat pictures can provide certain depth cues to the viewer, these cues are also referred to as *pictorial cues*. Some of them, such as linear perspective, relative size and occlusion, are related to the object's size or their relative positioning. However, the projection-based manipulation of these cues in a real-world SAR environment is difficult, since this requires to deform the apparent shape of the affected objects. In contrast, a second category of depth cues, the tone-related cues, seems to be more auspicious. This category contains all depth cues that are inferred from luminance distributions in a scene, for instance, shading and aerial perspective [23]. Since luminance variations only affect the surface characteristics of scene objects while their shape remains unchanged, tone-related cues could be modified in a SAR setup more easily than size-related ones. Hence, for our preliminary study we made a selection of three pictorial cues, which were rated as most practical in a SAR environment: color temperature, luminance contrast and blur. Besides these pictorial cues, which all work under monocular conditions, there are some other depth cues that rely on the binocular vision of humans. From this category we chose a fourth depth cue, the retinal disparity, to compare it with the monocular cues.

2.1 Color Temperature

When viewing an image that shows different colored objects within a dark surrounding, most people observe what is called chromostereopsis: warm colored objects tend to appear closer to the

(a) *Coquelicots* by Robert Vonnoh.   (b) *Worcester* by William Miller.   (c) *Rome, From Mount Aventine* by J. M. W. Turner.

Figure 1: Artwork featuring (a) color temperature, (b) luminance contrast and (c) blur as depth cues.

viewer while cool colored objects appear farther away (see Fig. 1a). The opposite effect can be perceived when the background is white instead [6]. Most researchers who considered the phenomenon in the past indicated a physiological cause for this visual illusion: When light enters the human eye, it is refracted depending on its wavelength. Shorter wavelengths, e. g., blue light, are refracted more than longer wavelengths such as red light. This effect is also referred to as chromatic aberration and reasons why short-wave light sources occur nearer than long-wave light sources when placed at the same distance to the viewer. In the past, several studies addressed the impact of an object's color to its perceived depth, although most of them focused on stimuli presented on a 2D display [3, 9]. In addition, a few perceptual experiments were conducted to investigate chromostereopsis in a real environment with different colored test objects [2] or light sources [12]. In all referenced setups a measurable effect of color on depth perception could be found.

2.2 Luminance Contrast

A second monocular depth cue that is related to an object's surface characteristics is the luminance contrast between the object and its background. In a real environment, light is scattered by particles in the atmosphere, resulting in a reduction of contrast when the viewing distance increases (e. g., [5]). This effect is called aerial perspective and can be observed for an object's texture and shading as well as the contrast between an object and its background. By manipulating the luminance values of adjacent regions, the characteristics of aerial perspective can be simulated and therefore an illusion of depth can be added to an image (see Fig. 1b). The systematic correlation between perceived depth and luminance contrast was first revealed by Egusa [8] and has been confirmed in several perceptual studies since then (e. g., [10, 13, 23]). Moreover, Oshea et al. [20] showed in one of their experiments that perceived depth is larger under monocular conditions in comparison to binocular ones. An interesting question would be whether these findings can be reproduced in a SAR environment.

2.3 Blur

Aerial perspective also accounts for the fact that relative sharpness of an object's outline decreases with an increasing distance to the observer. This blurring effect is amplified by the physiology of the human visual system. Since our eyes have a limited depth of focus, all object details, which are lying in front of or behind the focal plane with a too large distance, are blurred. The extent of blur depends on the distance between the object and focal plane and therefore blur can be used as a measure of depth. Studies suggest that blur can create a sensation of depth even in absence of any other cues and under monocular conditions [19]. Thus, blur is a commonly used technique in arts, photography and video editing (see Fig. 1c).

2.4 Disparity

The last considered depth cue arises from the fact that our two eyes have a slightly different view of the world, resulting from the interpupillary distance. The human brain uses the difference in locations of an object point in the left and right eye's image, also called the binocular disparity, to infer the egocentric distance of this object point. Binocular disparity is a quantitative representation of depth and therefore is often claimed to be one of the strongest depth cues. Because of that, we aim to investigate the effectiveness of this binocular cue in a SAR setup and compare the results to the performance of monocular cues.

3 SAR TESTING ENVIRONMENT

Since SAR is an emerging area of research, there is only a small number of reported perceptual studies, which were conducted in a SAR context. Therefore, we cannot draw on prior knowledge regarding the ideal setup for conducting such studies. Furthermore, in comparison to virtual reality and see-through AR studies there are additional factors to be considered in order to meet the requirements of reproducible and ecologically valuable studies. To face these new challenges, we built up our own prototypic SAR setup (see Fig. 2).

We started from a slightly dimmed room, i. e., no direct sunlight interfered with the projection, which matches the conditions of most SAR installations to this day. For the purpose of testing the different illusions, any solid object with a light colored, non-textured surface is suitable, provided that its material reflects light diffusely in order to avoid specular highlights. For our prototype, we chose a styrofoam ball that was illuminated by a projector (Optoma HD20). In order to avoid reference points that might have an influence on the viewer's depth perception, we used a transparent fishing line to place the ball between two poles and therefore create the illusion that it is levitating. Overall, there were three pairs of poles, which made it possible to place the ball at three different distances from the viewer as well as the background. In order to realize changes in the background's luminance and color, we used a second projector in the form of a smartboard short-throw projection setup, which was placed behind the ball. We deliberately decided against using the same projector for both the foreground and background object, since the offset between the user's eyes and the projector produced shadows that potentially bias the results. By using two separate projectors, we were able to reduce this effect to a minimum. The third projector (Acer H5360) that can be seen in Figure 2 projected onto a table, which was situated beyond the levitating ball. It had a single purpose, namely the rendering of a small marker, which could be used to communicate the perceived depth of the ball later on. Via a connected mouse, the marker could be shifted along the z-axis, which corresponds to a movement towards the user or away from him, respectively. The user looked at the
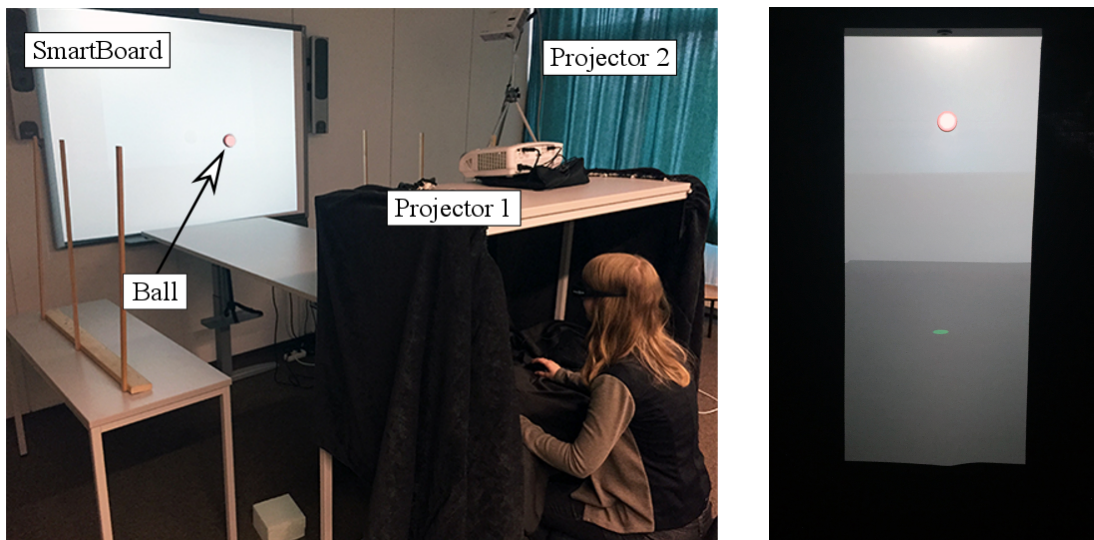
Figure 2: Illustration of the experimental setup (left) and the user's view (right).

entire setup from the front side while all construction details and projectors were hidden by a mask. In a final step, a chin rest was mounted in front of the setup in order to relieve the user and fix their head's position at the same time. By stitching all parts together, we developed our prototypic setup for SAR experiments as depicted in Figure 2.

4 PRELIMINARY STUDY

For our preliminary study we aimed for two goals: First, we wanted to expose our prototypic SAR experimenting environment to a practical test in order to identify issues, which can be improved in an iterative development process. Second, we intended to get a first impression of whether the formerly described depth cues can be used in a SAR environment to change the perceived depth of an object.

4.1 Methods and Protocol

We invited 17 participants, 14 male and 3 female (aged from 24 to 64, $M = 36.5$). The participants were members of the department of computer science at our university. All of them had normal or corrected-to-normal vision. We confirmed each participant's ability to perceive binocular depth with stereograms before the experiment.

At the beginning of the experiment, the participants were guided with a blindfold into the position shown in Figure 2. Afterwards, the participants received detailed instructions on the depth estimation task they were required to perform.

For the main part of our study, we followed a repeated measures within-subjects design. The independent variables were the number of used eyes (E), the real distance between the user and the ball (D), the applied illusion (I) and the gain of this illusion (G).

In order to test the illusions both under binocular and monocular conditions, the experiment was divided into two blocks. In the first block, the participants wore shutter glasses while in the second block they had to cover their non-dominant eye with an eyepatch.

Within each block, three distances at steps of .5 meters in two meters, were considered. We did not alternate between these distances, since the ball had to be moved manually in our prototypic setup, resulting in a high time exposure for every distance change. Instead, all conditions for a specific configuration $(E_i, D_j)_{i \in \{1,2\}, j \in \{1,2,3\}}$ were processed in a row, while the order of the distances was randomized between participants.

When implementing the four illusions that were introduced in Section 2, we followed the approach of Bailey and Grimm [4]. In a perceptual study the authors showed that modifying only the boundary of an object as well as the background can be sufficient to change the observer's depth perception. Since we intended to manipulate the real scene as little as possible, we decided to adopt this technique for the color temperature, luminance contrast and blur illusion. For the remaining depth-from-disparity cue a golf ball texture was applied to the ball. This effect was skipped in the second part of the experiment, which relied on monocular vision.

For every illusion, four different gains were chosen as illustrated in Figure 3. The gains represent different effect levels, which we designed choosing color, luminance, blur and disparity parameters for the sign and scale of the illusion as shown in Figure 3. However, it should be noted that the gains can not be considered to be equidistant. According to the literature, it can be expected that some of the pictorial cues are interpreted differently from observer to observer, e. g., whether the brighter or the darker of two test objects appear nearer. In addition to the illusion-specific gains, one baseline condition was inserted for every distance. For this condition no effect was applied to the ball, so systematic underestimations or overestimations of depth can be revealed and subtracted from the results later on.

Overall, every participant completed 90 different conditions (E, D, I, G) and, since every condition was repeated, 180 trials in total.

At the beginning of each trial, the marker was located at a randomly picked position and the ball as well as the background were illuminated according to a randomly chosen condition. Afterwards, the participants had to position the marker exactly underneath the ball by scrolling the mouse wheel. When they confirmed the marker position, a new condition was chosen. For every trial we logged the estimated distance, which acts as the dependent variable in our study.

After completing all trials, every participant filled in a questionnaire that requested both demographic data and qualitative feedback. Overall, the study took around 40 minutes per participant.

4.2 Results

We analyzed the results with repeated-measure ANOVAs and multiple comparisons with Bonferroni correction at the 5% significance

(a) Illusion 1: Color Temperature

(b) Illusion 2: Luminance Contrast

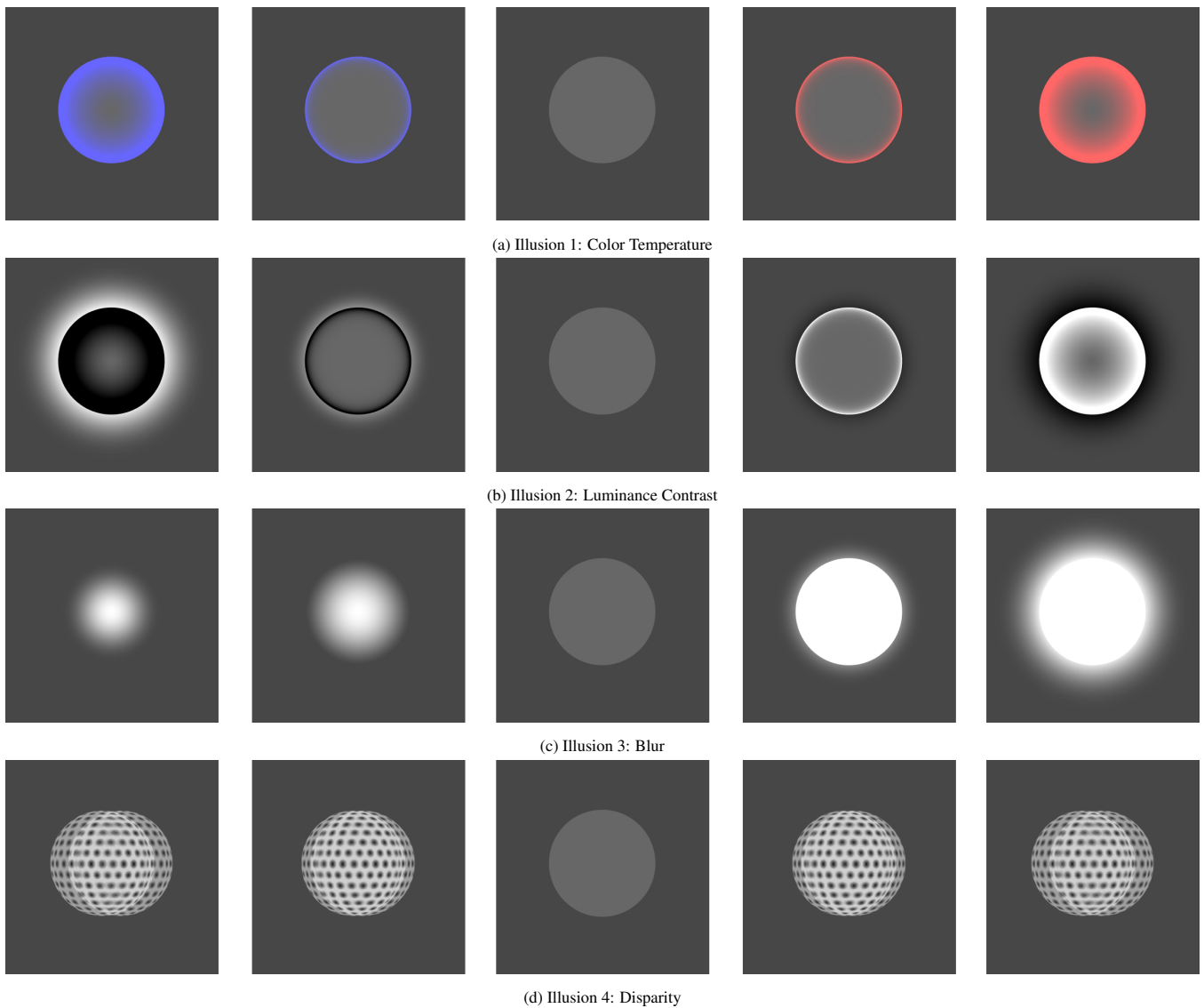(c) Illusion 3: Blur

(d) Illusion 4: Disparity

Figure 3: Illustration of the four projected illusions with four gains each (-2/-1/+1/+2). A gain of 0 corresponds to the baseline.

level. We confirmed the assumptions of the ANOVA for the experiment data. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity had been violated.

Figure 4 shows the pooled responses plotted as judged distances relative to the baseline distance in percent. The baseline distance is the distance which participants indicated in the real-world condition without illusory stimulation.

We found no significant difference between the relative judged distances in the monocular and binocular condition.

In the binocular condition we found a significant interaction effect between illusion and distance on relative judged distances, $F(6, 96) = 4.59$, $p < .001$, $\eta_p^2 = .223$, and between illusion and gain on relative judged distances, $F(3.7, 59.4) = 10.39$, $p < .001$, $\eta_p^2 = .394$. Furthermore, we found a significant main effect of gain on relative judged distances, $F(1.8, 28.1) = 4.88$, $p = .018$, $\eta_p^2 = .234$. No other main effect or interaction effect was significant.

In the monocular condition we found a significant main effect of gain on relative judged distances, $F(3, 48) = 5.18$, $p = .003$, $\eta_p^2 = .245$. No other main effect or interaction effect was significant.

4.3 Discussion

Overall, the results of our preliminary study provide positive indications that distance judgments in a SAR environment can be changed with illusion techniques. In particular, under the binocular conditions, retinal disparity showed the strongest effect for all tested distances, which aligns well with results from previous studies in augmented and virtual reality environments. Moreover, for the longest distance, blur seems to be the most effective pictorial technique. Based on this observation, it can be hypothesized that the application of blur will allow the modification of perceived depth for even longer distances. However, further perceptual studies under SAR conditions are necessary to fully understand the approaches and their effects on spatial estimation.

Under the monocular conditions, we observed a comparably high standard error. This confirms previous studies, which claim that binocular disparity is the most important depth cue for the human
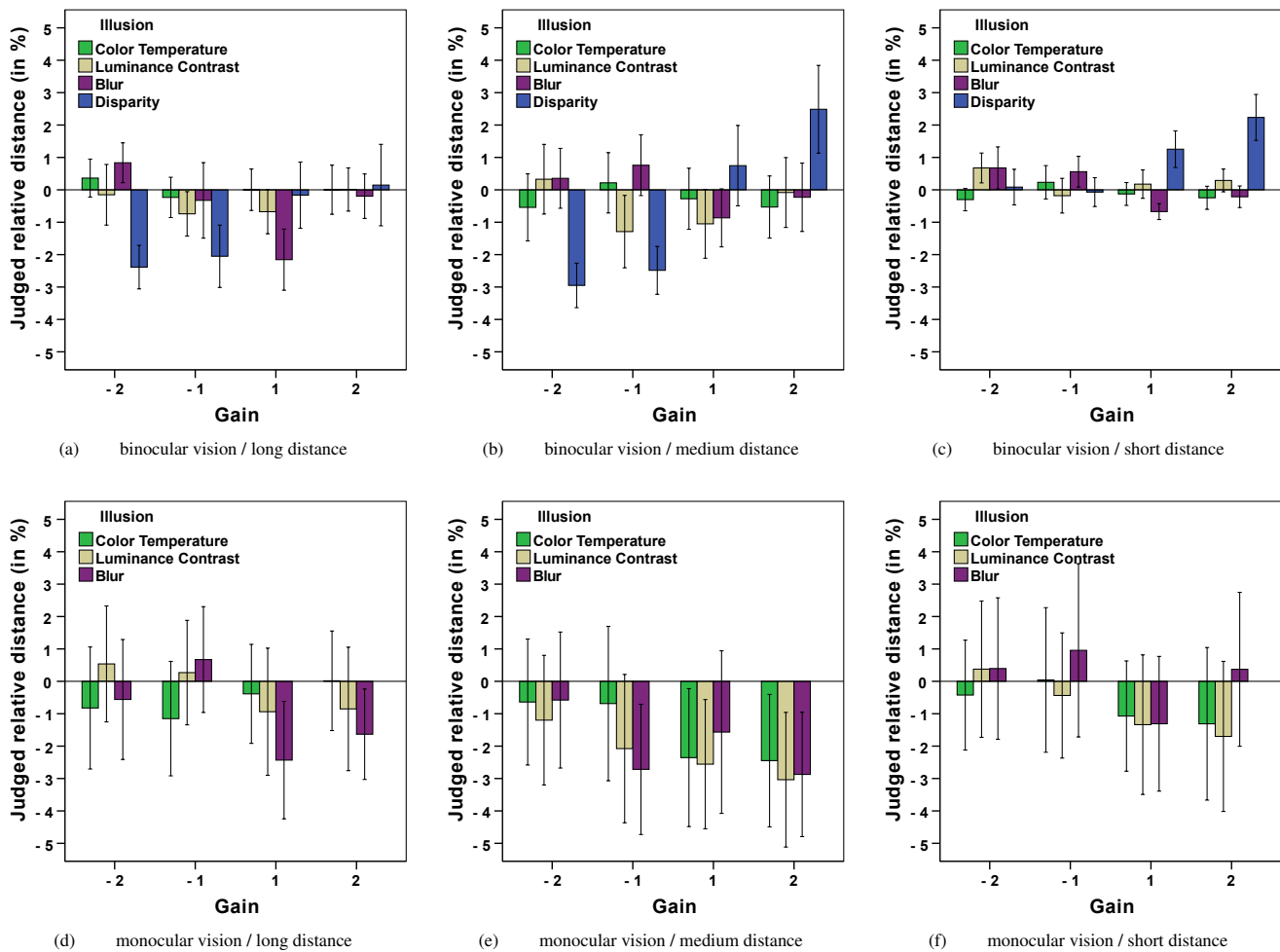
Figure 4: Results of the estimated distances for binocular and monocular vision with three different distances each. The vertical bars show the standard error.

visual system in close range [16]. The correct estimation of distance of an object proved difficult in the conditions in which the visual system could not make use of this cue in the study. In general, for most conditions a depth underestimation can be noticed when one eye of the participant was covered.

Limitations

A few limitations of our prototypic setup can be inferred from the informal qualitative feedback, which was given in the concluding questionnaire, and which provides practical insights for the development of future SAR experimental setups for perceptual studies.

According to the qualitative feedback, five of our participants stated that in some trials they estimated the ball's position even closer or farther than the marker could be moved on the horizontal table below the floating ball. We did not anticipate this for the tested distances before running the experiment, since this would correspond to an underestimation or overestimation of more than half a meter in depth.

Moreover, one participant reported in the condition with the retinal disparity technique that he perceived a superimposed golf ball in front of the physical one and therefore estimated the depth of this virtual ball. This indicates that the manipulation of perceived depth in this condition might additionally be limited by whether or not participants perceive one or two targets; a large discrepancy in depth might favor the perception of different objects.

Furthermore, the participants were asked if they used or developed any particular cognitive strategy to complete the depth estimation task. Five participants answered that they compared the current illusion to that seen in the previous trial and tried to judge the relative difference in depth, which implies that future studies should include interstimulus intervals, such as based on change blindness [22], to reduce such effects.

5 CONCLUSION

In this paper we presented a study to investigate whether perceived spatial relationships between the user and real-world objects can be manipulated by introducing perceptual illusions to a SAR environment. For this purpose we made a selection of four illusions, which are well-known from visual arts and filmmaking: color temperature, luminance contrast, blur and binocular disparity. The results of the study suggest that perceived depth of objects can be affected by projected illusions, although binocular vision dominated the other cues in all tested distances.

Along with the preliminary study, we developed a prototypic setup for conducting perceptual SAR experiments. Currently, we are working on an improved setup, which allows the automated positioning of objects in submillimeter range using a robotic arm. Based on this setup, we expect an increased accuracy, less manual work and a higher robustness. Furthermore, studies with more than three distance levels will be feasible in an appropriate timeframe.

Since the distance levels can be alternated more easily, this will also prevent users from applying strategies that involve the comparative depth estimation of subsequent conditions.

Other issues for a further development of our setup are the proper alignment of foreground and background effects for different users as well as the prevention of shadows. In our prototype we addressed these issues by using a chin rest with a known position and by placing the main projector close to this rest. Although these measures resulted in a reduction of both described effects, they can still be improved. With the integration of upcoming technologies like projection-enabling AR glasses, such as based on TechnicalIllusion's CastAR, both challenges could be met in the future.

Considering the results of our preliminary study, we have to deal with the separated perception of the real and a virtual object, which sometimes occurred when the binocular disparity illusion was applied to the ball. This phenomenon can be attributed to a more general problem, namely the projection of stereoscopic content onto non-planar surfaces. Since an object-covering effect would need to project images across the object's edges, it has to be investigated which perceptual consequences such a projection would imply. In our future projects, this will be a main issue for SAR research.

Finally, with an improved SAR testing setup all requirements for advanced tests on depth changing illusions are complied. This involves objects that are more complex both in shape and material. For example, the presence of textures is expected to have a strong impact on the results. Additionally, the intensity of already tested effects can be varied in a broader range. In the preliminary study an arbitrary percentage of the object's surface was affected by the four illusions. However, it would be desirable to figure out the best tradeoff between the effect of modifications on the estimated depth and the conspicuousness of these modifications. In particular, regarding the fourth illusion that is based on binocular disparity, one interesting option is to apply the Cornsweet illusion as shown by Anstis and Howard [1], which we aim to investigate in SAR environments.

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