THE EFFECT OF AMBIENT ILLUMINATION LEVEL ON PERCEIVED AUTOSTEREOSCOPIC DISPLAY QUALITY AND DEPTH PERCEPTION

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Abstract

Twenty participants viewed real-world videos with a small hand-held autostereoscopic device in three ambient illuminations with three display luminance levels. Perceived depth, naturalness, viewing experience, presence experience and discomfort were evaluated with two videos. The results show that illumination and luminance levels influence perceived quality parameters, but perceived depth is less sensitive to changes in ambient illumination than other parameters associated with 3D image quality. 3D presentations were immersive and realistic, which enabled exploration of the 3D world. Some mild visual strain symptoms were reported as a result of viewing scenes for 40 minutes. In conclusion, the use of auto stereoscopic hand-held devices seems feasible in different contexts with different display luminance levels, and the overall experience is enjoyable and immersive.

Keywords: 3D, auto stereoscopic display, perceived depth, naturalness, viewing experience, sickness, visual strain, presence

1. INTRODUCTION

As stereoscopic displays become more common, the issues related to various possible uses become more relevant. For example, if a mobile device has an autostereoscopic display, the display should be usable in various illuminance conditions ranging from a dim living room in the evening to bright sunlight in the daytime. High illuminance situations are problematic especially because they reduce the contrast of the display unless it has reflective components. Further, a large difference between the display luminance and the illumination level of the environment can reduce the visibility of the display, leading to sensations of discomfort or transient adaptation effects from fixating back and forth between two luminance levels [e.g., [1],[2]]. Chakrabarti, Kaczmarek, Thomas, and Romanyukha [3], among others, observed that room illuminance affects the intensity ratio of maximum to minimum monitor luminance. According to the authors, the consequent loss in the contrast ratio causes image contrast degradation. Even though a high contrast ratio is achieved when a very low monitor surround luminance of 0%–5% of the maximum is used in low ambient light of 5 lux or less, an increase in room illuminance can drastically reduce image contrast. Sheedy et al. [[1]] tested the effects of the luminance surrounding a computer display and showed that performance decreased at lower levels of surround luminance whereas higher surround luminance levels showed no effect on transient adaptation. Optimal performance was attained for surround luminance levels that were equal or higher than the display luminance. When participants were able to adjust the surround luminance level, they selected a luminance that was slightly less than the central luminance at 91 cd/m², but the preferred levels varied widely across the subject sample.
In addition to ambient illumination conditions, other parameters, such as display luminance, contrast levels, and sharpness may affect the perceived quality and subjective outcome. Fujine and colleagues [[4]] studied the relationship between preferred luminance and TV screen size. According to their results, the participants preferred lower luminances when the television size was larger. Further, lower environment illuminance lead to lower luminance preferences in the television screen. For example, when the display was located at a distance of three times the absolute display height (3H) and the screen illuminance was 180 lx, subjects preferred a luminance of 240 cd/m². Näsinen and Ojanpää [[5]] studied performance with user interface icons and found that one’s perception of icons is quite resistant to small or moderate decreases in contrast and sharpness, but hypothesized that in performance, high illuminance outdoor conditions might have a greater effect on icon perception.

1.1 3D quality: subjective evaluations

The image quality of three-dimensional images is fundamentally more complex than that of two-dimensional images, as the depth dimension creates a much richer and more engaging experience for the participants, and multiple parameters, such as depth reproduction quality and 3D-specific impairments, affect the final quality experience [[6],[7],[8],[9]]. According to Seuntiëns [[10]], image quality, depth, naturalness and visual comfort best describe the overall 3D visual experience (see also [[11],[12]]). Naturalness incorporates more image quality than does a viewing experience in which only the perceived image quality varies, rather than the degree of depth. In cases where depth varies, naturalness takes the added value of depth more into account than does viewing experience. The difference between naturalness and quality as a subjective evaluation concept lies in the fact that naturalness refers to what observers perceive as a truthful representation of reality (i.e., perceptual realism), whereas perceived quality refers to a subjective preference scale. For example, IJsselsteijn et al. [[13]] reported that the use of disparity information not only increases the ratings of perceived depth, but also affects the naturalness of depth. Seuntiëns, Vogels, and van Keersop [[14]] investigated the concepts of naturalness, viewing experience, and presence in relation to image quality, depth, and Ambilight technology in the context of 3D television. According to their results, the concept of viewing experience takes into account the quality level of the video as well as enhancements such as 3D and Ambilight. Moreover, depth and dynamic Ambilight provide the viewer with more sensory information, which results in a higher sensation of presence.

Luminance and contrast also affect a person’s ability to differentiate depth levels. Glabe and Baumann [[15]] tested the effect of luminance and contrast on stereoscopic acuity by using a three-rod arrangement. According to their results, moderate contrast (C=0.5) produced significantly lower thresholds of binocular depth perception than did low (C=0.05) and high (C=0.95) contrast with a fixed luminance level (250 cd/m), whereas different luminance levels (50, 250, and 1600 cd/m²) showed no effect on the depth perception threshold.

In addition, parameters such as JPEG coding and spatial low-pass filtering may lower perceived image quality in several ways, but they do not necessarily influence perceived depth [[10],[16]]. Moreover, Boydstun et al. [[17]] showed that a fairly large range of intraocular luminance levels could be used and still result in good stereo depth perception. In sum, some parameters (e.g., contrast level) seem to affect perceived depth while changes in other parameter (e.g., low-pass filtering) do not necessarily affect the quality of perceived depth.

1.2 3D-related presence experience

Several papers have connected 3D graphics to the presence experience (e.g., [[18],[19],[20]]). Witmer and Singer [[21]] defined presence as a subjective experience of being in one place or environment, even when one is physically situated in another (see [[22],[23],[24]]). According to the authors, both involvement (a psychological state experienced
as a consequence of focusing on a set of stimuli or meaningful activities) and immersion (the perception of being enveloped by, included in, and interacting with an environment) are necessary to create a presence experience. Even though emotional involvement and presence experience are often associated with interactive 3D environments, non-interactive tasks, such as movie viewing, TV or viewing 3D motion scenes, could also evoke a stronger sense of presence than could still stimuli or non-stereoscopic viewing conditions \([25],[26],[27]\). Moreover, the majority of published papers on 3D viewing experience, comfort, and usability have used relatively large display sizes \([26],[27],[28]\). IJsselsteijn et al. \([26]\), for example, used in their studies a projection display with a 50-deg horizontal field of view. The studies of Freeman et al. \([28]\) used a 20-inch stereoscopic screen with an effective horizontal field of view of 28 deg, while Pölönen et al. \([27]\) evaluated a 3D-related presence experience with a full-size cinema screen. In addition to the size of the display studies have shown that the type of technology used also affects subjective presence ratings \([26],[29]\).

### 1.3 Sickness and visual strain

Many tasks in everyday life, such as doing detailed work, reading small print, or long-term computer-related work, can contribute to visual fatigue and induce symptoms such as eyestrain, watery or dry eyes, a feeling of pressure when the eyes are open, hot eyes, difficulty focusing or blurred vision, and headaches (see \([30],[31],[32]\)). In the context of 3D applications and devices, several research results have reported eyestrain and changes in visual functioning as a result of viewing stereoscopic presentations (e.g., \([18],[33],[34],[35],[36]\); for an overview \([30],[37]\)). Yano et al. \([33]\), for example, found that people experienced more eyestrain with dynamic 3D screens than with static ones. Kooi and Toet \([7]\) found that even a limited vertical disparity, crosstalk, and blur could cause noticeable viewing discomfort while viewing stereoscopic static images. Among other recommendations, the authors suggested that lenticular screens should only be used to display stereo images with limited disparity to avoid viewing discomfort resulting from the combination of crosstalk and luster. Moreover, the results of Häkkinen et al. \([38]\), who utilized a mobile phone with a parallax barrier autostereoscopic display, indicate that utilizing small disparities is an effective way to avoid visual strain.

In addition to visual fatigue, immersion in a 3D VE could induce sickness symptoms, such as nausea and discomfort (see \([38],[39],[40]\)). Häkkinen and colleagues \([38]\) reported significantly higher sickness scores as a result of wearing a 3D head-mounted display than from a bi-ocular HMD or CRT display. Moreover, the nature of the task used to study subjective experiences clearly influences the outcome. For example, motion scenes can evoke illusory feelings of self motion (i.e., vection) and as a result, the user might experience sickness-like symptoms \([41],[42],[43]\). On the other hand, motion scenes could increase presence experience \([44]\).

In conclusion, added depth information influences perceived image quality and naturalness, and contributes to the sense of presence. In addition, depth magnitude, binocular image imperfections, and certain tasks may induce eyestrain and sickness. Because hand-held devices can be used with several different applications in many different contexts, it is important to ensure that new features will meet users’ expectations and induce no serious health-related problems. Our main goal was to investigate different subjective outcomes related to the usage of a stereoscopic handheld device. On a more detail level, we focused on depth perception, naturalness, overall viewing experience, discomfort, and presence experience with different illumination and display luminance levels.
2. METHODS

2.1 Procedure

Each test session began with a short introduction to the experiment followed by visual screening (visual acuity near, stereo acuity, and color vision). Thereafter, participants were asked to complete the Simulator Sickness Questionnaire (SSQ; [[39]]) and a Visual Strain Questionnaire (VSQ; modified from [[45]]). The SSQ is a 16-item symptom checklist for measuring simulator sickness. Each symptom is rated by the individual as either "none," "slight," "moderate," or "severe". The total severity factor determines whether a sickness problem exists, and subscales for nausea, disorientation, and oculomotor symptoms level provide more specific information about the nature of the sickness. The Visual Strain Questionnaire measures the severity of eyestrain symptoms (tired eyes, sore or aching eyes, irritated eyes, watery or runny eyes, dry eyes, hot or burning eyes, blurred vision, double vision, general visual discomfort) often connected to computer vision syndrome [[46]] as well as to the use of 3D displays [[7],[37]]. In the background questionnaire, we asked questions about factors that could contribute to sickness and discomfort (e.g., age, gender, headache history, motion sickness susceptibility, medication, and previous experience with 3D devices). In the next step, the participants were asked to view two videos (display luminance 102.87 cd/m², illuminance 30 lux) one at a time and to evaluate perceived depth, naturalness and overall viewing experience on a scale from one (bad) to ten (excellent) (see [[10]]). The laboratory illumination and device luminance levels were chosen on the basis of preliminary expert evaluations with three people. In the School video (length 25 seconds), a group of people discuss and change their positions, while in the Quarrel video (length 29 seconds), three boys quarrel (see Fig. 1). The movie was filmed with two HD video cameras. Camera mounting allowed adjustment of the camera separation from 37 mm to 140 mm. Cameras were set up in parallel to minimize any possible vertical disparity. Camera focus and alignment were checked to allow for later elimination from the film of material distortions and artefacts arising from differences between the cameras. A tripod with a water level was used to film the "School" take, and for the "Quarrel" take, the cameras was partly held in hand. The film was specifically designed for comfortable viewing in a hand-held device. After practicing, the participants viewed both scenes at three laboratory illumination levels (dim home: 30 lux=A1, office: 450 lux=A2, outdoor: 3300 lux=A3) and at three display luminance levels (9.73 cd/m² (3D crosstalk 3.68%, 3D contrast 210); 21.36 cd/m²² (3D crosstalk 3.44%, 3D contrast 198); 102.87 cd/m²² (3D crosstalk 3.57%, 3D contrast 201) (3 laboratory illuminations * 3 device luminance * 2 scene contents * 2 repetitions * 3 questions). Altogether each participant viewed and rated 36 video sequences. Subjects provided their responses by stating them aloud, and the test leader recorded them on a separate answer sheet. The presentation order of the laboratory illuminance and device luminance levels was fully randomized between the subjects. The tests were carried out in a light simulator laboratory. Test leader manually changed the device luminance and laboratory illuminance levels. After viewing all the scenes, the participants again completed the SSQ and VSQ questionnaires in addition to the presence-related questions, questions of task pleasantness, task interest and change of opinion. At the end of the test session, the participants and the test leader had the opportunity to ask questions and comment on the experiment. The test session lasted approximately one hour, and the participants were rewarded with movie tickets.
Fig. 1. Examples of the video scenes used: Quarreling (left) and School (right).

2.2 Equipment

The 3D display used in the experiment was a small-size (4.13") high-resolution two-view autostereoscopic display (with a lenticular lens as the stereo structure) integrated into Nokia Internet Tablet N810, which features a display resolution of 800 x 480 pixels. The optimum viewing distance was approximately 40 cm, but the test participants were encouraged to adjust the viewing distance themselves for the best possible 3D experience. Optical characterization methods were employed according to Järvenpää and Salmimaa [[47]] to quantify the display parameters that were changed during the course of the test. The 3D luminance levels for the display were measured for each of the backlight settings used during the test. Luminance measurements were carried out with a conoscope. The angular range for the measurement was from -60 degrees to 60 degrees, and the angular step size was 0.5 degrees. The angular luminance profiles for each of the views were measured (the view of interest was white, and the other view, black), and the same procedure was repeated for all of the backlight settings. In Figure 2 shows the results of the angular range from -15 degrees to 15 degrees. The 3D crosstalk and the contrast ratio were determined from the luminance profiles obtained.

Fig. 2. Luminance profiles for the two-view auto stereoscopic display used in the test (L1=9.73 cd/m², L3=21.36 cd/m², L5=102.87 cd/m²).

2.3 Participants

Altogether 20 subjects participated in tests (9 males and 11 females aged 25–58 years; mean 38.4 years). 18 of whom had previous experience with 3D applications (including 3D cinema visits). Most of the participants were rarely susceptible to motion sickness (75%) or headaches (75%). All the participants had normal or corrected-to-normal visual
acuity and a stereo acuity of 30 sec-arc or better (tested with the TNO test for stereoscopic vision). Participants who wore prescription lenses for near work also wore them in the test.

3. RESULTS AND DISCUSSION

We used the GLM Univariate, Kendall’s tau-b test, Wilcoxon signed-ranks test, Kurskal Wallis test, and Mann-Whitney U test in the statistical analysis of the results.

3.1 Perceived depth, naturalness, and overall viewing quality

The Univariate ANOVA test revealed significant differences in perceived depth, naturalness and viewing quality between the illuminance levels (F(2)=39.625, p<0.001) and screen luminance levels (F(2)=196.113, p<0.001), as well as between responses to the questions about quality (F(2)=50.955, p<0.001). In addition, we found significant interactions between screen luminance levels and illuminance levels (F(4)=27.094, p<0.001) (see Fig. 3a), between illuminance and video content (F(2)=6.058, p<0.01) (see Fig. 3d), and between screen luminance levels and quality-related questions (F(4)=4.067, p<0.01) (see Fig. 3b).

Because of the differences in luminance level scores with different illumination levels (see Fig. 3a), we conducted an ANOVA and post-hoc comparison separately for each luminance level. The ANOVA revealed significant differences in reported scores when screen luminances of 9.73 cd/m² (F(2)=51.684, p<0.001) and 21.36 cd/m² (F(2)=3.233, p<0.05) were used with different illumination levels. The results (Tukey HSD) indicate that when a luminance of 9.73 cd/m² was used, laboratory illumination reduced the overall perceived quality of the stereoscopic videos (30 lux/450 lux,
p<0.001; 450 lux/3300 lux, p<0.001; 30 lux/3300 lux, p<0.001). On the other hand, when a luminance level of 21.36 cd/m² was used, only 30 lux and 3300 lux quality scores differed significantly (p<0.05). No significant differences were found with an luminance of 102.87 cd/m². Moreover, the overall quality levels were significantly lower with a luminance of 9.73 cd/m² than with luminances of 21.36 cd/m² (p<0.001) and 102.87 cd/m² (p<0.001). Overall viewing experience and naturalness were rated lower than perceived depth with all luminance (Fig. 3b) and illuminance (Fig. 3c) levels (depth vs. viewing experience, p<0.001; depth vs. naturalness, p<0.001). In addition, the overall quality (including depth, naturalness, and viewing experience) scores remained relatively stable when 21.36 cd/m² and 102.87 cd/m² were used with different laboratory illuminations (see Fig. 3a), whereas the use of 9.73 cd/m² reduced the reported quality levels as illuminance increased. As Figure 3d shows, the video content slightly affected the reported quality scores as illuminance changes. Because both videos used in the test represent interaction between groups of people, the quality changes reported seem to take into account relatively small differences within 3D scenes, which appear to be especially sensitive to context illumination and to cause different effects with different illuminations.

3.2 Sickness and visual strain

A comparison of symptom levels using the Wilcoxon signed-ranks test both before and after the task clearly revealed higher visual strain levels after the task (VSQ; higher scores mean more/stronger symptoms) (Z=-2.170, p=0.03). No other significant changes in other symptom levels (SSQ) were found. The result is similar to those of other studies, which have shown that participants may experience visual discomfort and eyestrain as a result of viewing stereoscopic images (e.g., [7],[18],[30],[33],[34],[35],[36]). Because the videos used in the test contained no strong motion scenes, which are often connected to experiences of sickness and discomfort, no one reported symptoms of nausea or disorientation. As Figure 4 shows, more than half of the participants reported no any changes in visual strain-related symptoms, and only four participants reported more than one symptom. In sum, viewing stereoscopic content on a hand-held auto stereoscopic display for as long as 40 minutes appears to cause no serious discomfort.

![Fig. 4 Change (x=post-pre) in visual strain symptoms after viewing (new symptom or a stronger level of a current symptoms≥+1, fewer symptoms≤-1, no change=0).]
3.3 Presence experience

Over the years, several factors have been hypothesized to contribute to a sense of presence. For example, the degree of one’s interaction with and control over a task, one’s ability to modify physical objects in VE, environmental richness, multimodal presentation, the meaningfulness of the experience, scene realism, and the consistency of information with the objective world have all been found to affect the degree of presence reported [21,48,49]. Because of the nature of the videos (small format short scenes without audio, high resolution 3D natural content) and of the experiment set-up used (repetition of the same videos, no interaction or personal meanings), we selected only a few presence-related questions (see [27]) which seemed to elicit important 3D-related views of the presence experience. As Figure 5 shows, participants rated the scenes in the 3D world as highly credible compared to the scenes in the real world (mean=5.45, minimum=3, maximum=7). Moreover, they felt that they were able to explore the 3D world (mean=5.6, minimum=3, maximum=7), and that the characters of the 3D videos felt real (mean=4.95, minimum=3, maximum=7). In addition, participants felt immersed in the 3D presentation (mean=4.9, minimum=3, maximum=6) and the scenes triggered some real emotions in viewers in the absence of interaction, control, or other factors connected to the experience of immersion (mean=4.2, minimum=1, maximum=6) [21]. Following the 3D presentation was easy, but due to the lack of interaction and other factors, the participants never got the impression that the 3D movie characters were aware of them (mean=1.9, minimum1, maximum=4). In sum, even though the participants viewed short video clips on a small hand-held autostereoscopic screen with no audio or interaction, high quality real-world content can trigger strong feelings of realism and presence. Moreover, the participants’ opinions about 3D presentations clearly became more positive after the test (my own opinion about 3D presentations changed because of this test from 1 (Clearly more negative) to 5 (Clearly more positive); mean=4, minimum=3, maximum=5), and the majority of the participants were surprised by how realistic and high quality 3D presentations are today (open questions). In addition, the participants enjoyed the task (from 1 to 5; mean=3.65, minimum=2, maximum=5) and evaluatated it as rather interesting (mean=3.4, minimum=2, maximum=5).

![Mean scores for presence experiences. Scene credibility* was scored by using anchors from totally incredible (1) to very credible (7). Vertical lines represent standard errors.](image-url)
4. CONCLUSION

Twenty participants viewed and rated two short 3D videos on a autostereoscopic display with three laboratory illuminations and display luminances. All the quality ratings (i.e., perceived depth, naturalness, and overall viewing quality) were affected as illuminance and luminance levels changed. All the display luminance levels appear to be usable at dim illuminance levels, but in outdoor conditions, higher display luminance levels are preferable (see Fig. 3a). Viewing the 3D scenes caused some mild visual strain symptoms, but none reported nausea or disorientation. The majority of participants evaluated the 3D experience as immersive and highly credible compared to real-world scenes. The participants felt they were able to explore the 3D world, and the characters of the 3D videos felt real to them. As a result, the participants were positively surprised by the 3D quality and the overall viewing experience.

From the point of view of small hand-held devices these results are encouraging. The sense of presence can be increased, even though it has previously often been connected to larger screen sizes. The effect of illumination changes on the quality evaluations shows that devices can be used in different contexts with different illuminations and that it is possible to save energy or to adjust image quality and naturalness by changing device luminance levels. It seems that the use of real-world 3D scenes is enjoyable, and that these results could be applied to many tasks, including mobile TV, movie viewing, videoconferencing or peer-to-peer interaction. In addition, it seems that a viewing duration of up to 40 minutes causes no serious health-related problems. In conclusion, subjective experiences with small hand-held 3D auto-stereoscopic devices using real-world content are promising, but more research and development is needed to assure high-quality, positive experiences in the future with other task-, user- and technology-related variables.

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