One step closer to a better experience: analysis of the suitable viewing distance ranges of light field visualization usage contexts for observers with reduced visual capabilities

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ABSTRACT

Light field visualization technology offers a glasses-free 3D experience that may be enjoyed by multiple observers simultaneously. The overall visual experience depends on a multitude of factors, among which is light ray density. In case of horizontal-only parallax displays, it defines the smoothness of the horizontal motion parallax, which is crucial to visualization quality. However, the perceived light ray density naturally depends on the viewing distance; the farther the observer is, the fewer light rays may address the two pupils, with respect to a single point on the screen. Research on this topic has already been initiated and the first results are now available in the scientific literature. However, the experiment, similarly to the vast majority of research efforts regarding the perceived quality of light field visualization, is built on the participation of individuals that are screened for normal vision. Yet a notable portion of potential future users would not pass such screening, particularly the Snellen chart on visual acuity. In this paper, we investigate the suitability of viewing distances for the future use cases of light field visualization from the perspective of users with reduced visual capabilities. The subjective tests evaluate contexts of passive visual consumption, such as a cinematic experience or an exhibition of cultural heritage. The selected use cases are not only assessed by their natural viewing distance intervals, but by closer and farther distances as well. The output of the research aims to extend the social inclusion of potential systems and services of light field visualization.

Keywords: Light field visualization, viewing distance, human visual system, use-case-specific preference

1. INTRODUCTION

Throughout the past two decades, projection-based light field displays have emerged. At the time of writing this paper, they are already available for use in the industry and for academic research; however, it needs to be noted that they have not yet appeared on the consumer market and they are still quite far from becoming a part of our everyday lives. Nonetheless, the significant research efforts of the scientific community and the industry continuously and tirelessly contribute to the quality-focused development, the resource-efficient manufacturing and the user-centric optimization of such devices.

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Speaking of quality, the visualization quality and the practical performance of light field displays may be assessed via a multitude of metrics. Yet, at the end of the day, what really matters is that the users are satisfied. Of course, satisfaction is enabled by the display's ability to fulfill the requirements set by the use case in which it is deployed.

The use cases of light field visualization may be characterized by content type, required display parameters (e.g., screen size, resolution values, valid viewing area, etc.), human-computer interaction (HCI), viewing distance, and many more. The latter is home to particularly interesting research questions, since it is directly connected to technical parameters. Technically speaking, the further an observer is from the plane of the screen, the lower light ray density one may perceive. Light ray density – commonly referred to as angular resolution – is essential to the 3D experience, as through the angular nature of autostereoscopic visualization, a single point on the screen of a projection-based light field display may address the two eyes (i.e., pupils) of the observer with distinct light rays. Furthermore, it is also possible to address a single pupil with distinct light rays, resulting in the technical phenomenon called super resolution, which enables focusing within the 3D visuals.

Evidently, different use cases have different requirements regarding viewing distance. The most common approach is to determine the recommended maximum viewing distance by the angular resolution of visualization.[1] The principle is that human beings do not physiologically deviate much in terms of interpupillary distance – which is around 6.5 cm – and that this allows an estimation of a maximum distance at which two distinct light rays may address the two pupils, with respect to a single point on the screen. This also accounts for the possibility that the head of the observer has no sideways movement at all – which is very unlikely, but possible.

Angular resolution in the discussed topic refers to the horizontal angular resolution of the display and the visualized content. Practically, while the long-term development of light field visualization heads toward full-parallax (FP) imaging, today's systems are horizontal-only parallax (HOP) displays. They are considered sufficient for the majority of potential use cases, as the human eyes are horizontally separated, and user movement within use cases is typically horizontal (e.g., walking around a display system in an exhibition of cultural heritage).

Many research efforts have already been published on the topic of the Quality of Experience (QoE) of light field visualization, including the subjectively-preferred viewing distance. However, such subjective studies – similarly to all other types of visual QoE research – are typically carried out with the help of test participant screening, based on vision. This means that tests consider the subjective ratings of only those who qualify in terms of visual acuity and color vision.

In this paper, we present our study on the viewing distance of potential use cases of light field visualization, as perceived and preferred by individuals with reduced visual capabilities. The study fundamentally builds on our recently published findings,[2] which, according to the best knowledge of the authors, was the first to involve such users in light field QoE research. While the previous work investigated various test conditions, such as spatial resolution, angular resolution and viewing distance, the study presented in this paper was particularly designed to investigate the preferred viewing distance. Therefore, in contrast to the two viewing distances of the earlier work, the experimental setup of this research involved six. The six viewing distances were used to evaluate the quality of two combinations of resolution values. Furthermore, the test participants recruited for this study were not affected by deficiencies related to color vision. Instead, they had significant issues regarding visual acuity. Additionally, the evaluation was completed by an individual with a vision loss rate over 90%, the rating tendencies of whom are separately presented in this paper.

The remainder of this paper is structured as follows. Section 2 provides a review of the related scientific literature. The experimental setup is introduced in Section 3. The results of the subjective tests are presented in Section 4. The paper is concluded in Section 5.

2. RELATED WORK

The investigation of QoE-related research questions on light field visualization started roughly a decade ago, parallel with the emergence of the first commercially-available displays. While even at the time of writing this paper, the availability of real light field displays (which exclude autostereoscopic displays with so-called "sweet spots") to researchers is still greatly limited – as only a handful of institutions have access to such technology – many subjective studies have been carried out so far. According to the analysis of a recently published work,[3] a total of 29 studies have been published by the first quarter of 2022.

These studies cover the topics of resolution,[4–12] compression,[13] spatial distortion,[14,15] field of view (FOV),[16] interaction,[17,18] interpolation,[19] light field reconstruction,[20,21] view synthesis,[22] format assessment,[23,24] system assessment,[25] quality switching,[26] content orientation,[27] region of interest (RoI),[28] zoom levels,[29] viewing conditions[30] and viewing distance.[31,32]

The works on viewing distance rely on the following equation:

$$Viewing\ distance \leq \frac{Interpupillary\ distance}{tan(Angular\ resolution)} \quad (1)$$

As already mentioned in the introduction, the scientific community approximates the average interpupillary distance as 6.5 cm, and therefore, the angular resolution of the system and the visualized content directly determines the recommended maximum viewing distance (let us denote it by D_V). This D_V distance was used as a theoretical anchor during the design process of the experimental setup for both studies (i.e., the investigated viewing distances were chosen with particular emphasis on this given distance). Although the findings indicate notable deviation on the level of personal preference, the changes in binocular disparity are clearly reinforced by the results, and it was shown that this D_V distance is technically halfway between a 2D and a 3D visual experience.

The aforementioned 29 studies do not include our work on the perceived quality of light field visualization assessed by test participants with imperfect visual acuity and color blindness,[2] as it was published very recently. Since there were multiple test variables – and thus, each variable was limited to constrain the total duration of the test – only two viewing distances were used (with a 1-degree angular resolution): $0.5 \times D_V$ (1.86 m) and D_V (3.72 m). The rationale behind using $0.5 \times D_V$ was to ensure a viewing distance from which the visualized content may be perceived in proper 3D. Again, in general, viewing a content from a D_V distance without any sideways movement may provide a visual experience that is not clearly 3D, yet not flat 2D either.

The overall ratings reported in the study do not indicate a statistically significant difference between the two viewing distances, although it should be noted that for both test participant groups (color-blind individuals and those with issues related to visual acuity), the visualized contents with various resolution values were rated higher at the farther distance, particularly by the second group. It should be noted that the two groups included only 8 and 7 test participants, respectively. In this study, we solely focus on the second group, with nearly three times as many test participants – in order to reduce the impact of individual rating deviation and thus provide better circumstances for statistical analysis – and three times as many viewing distances – including $0.5 \times D_V$ and D_V.

3. EXPERIMENTAL SETUP

3.1 Light field display and environment

The subjective tests were carried out on the HoloVizio HV640RC large-scale back-projection light field display. The FOV of the display was calibrated to be 56 degrees. As common practice, the tests took place in a laboratory, which was isolated from audiovisual distractions and shielded from external light sources.

3.2 Test variables

The primary test variable was the viewing distance. As stated earlier, $0.5 \times D_V$ (1.86 m) and D_V (3.72 m) were used, and three more, evenly distributed distances (0.47 m between them) were also included between these two, plus one in front of $0.5 \times D_V$. Therefore, the six viewing distances were the following: 1.39 m, 1.86 m, 2.32 m, 2.79 m, 3.25 m and 3.72 m.

The initial D_V value was based on an angular resolution of 1 degree, which was the lowest angular resolution in the study. We used only two quality representations in this research. One was low resolution (640×480 spatial resolution and 1 degree angular resolution), and the other one was high resolution (1024×768 spatial resolution and 0.5 degrees angular resolution).

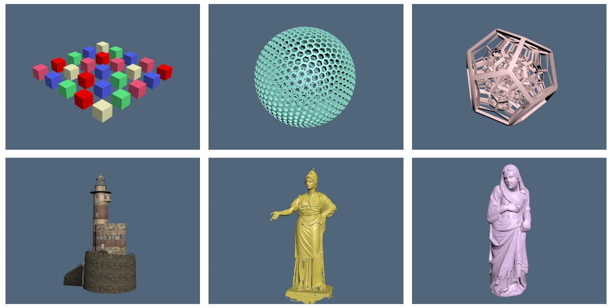

Figure 1. The source contents of the subjective study.

3.3 Source contents

The source contents of the study were similar to those of the prior work. However, while there were 8 contents previously, we reduced it to 6 in the current research in order to compensate the high number of viewing distances. They were static 3D objects in front of a plain background, diverse in content characteristics (e.g., structural complexity, model depth, etc.). The source contents are shown in Figure 1. The 6 contents included simple and complex objects (i.e., a set of cubes and structurally-dense mathematical bodies), a textured object and laser-scanned statues.

3.4 Test conditions and test stimuli

The test conditions were the combinations of the test variables. In this case, both representation qualities were assessed from every single distance. There were 12 test stimuli in total, as the 2 quality settings were applied to the 6 source contents. As there were 6 viewing distances, each test participant performed 72 quality assessments on the rating scale.

3.5 Rating scale

The study used the same rating scale as in the previous work. It was an Absolute Category Rating (ACR) scale with 10 rating options from 1 to 10. The worst and best possible scores were 1 and 10, respectively. However, there was a slight alteration in comparison to our prior research. While 10 represented the reference quality in that one, the same was simply the best score that could be given in this one. The reason for this modification is that there were only 2 quality settings in this study, one of which was actually the same as the reference quality in the previous work.

3.6 Test procedure and usage context

As it is a standard procedure, the test stimuli were presented to the test participants in randomized order. Once a stimulus was visualized, the test participant was asked to rate it from the 6 different viewing distances, which were marked on the floor. Simultaneous participation was not allowed in the study (i.e., only a single individual participated at a given time). The default viewing angle was the center view, from which the test participants could deviate only with minor sways of the head and the body.

The study aimed to cover usage contexts with a static observer model (i.e., the observer does not move while viewing the light field display). The most typical use case for this is cinematography, where an observer is assigned a given viewing distance and viewing angle for the entire duration of the content. It was an option to have seated test participants in this study; however, that could have been cumbersome for the test participants on multiple fronts. It would not have been possible to assign an individual chair to each viewing distance due to the smaller distance intervals. Additionally, such methodology would have required a very specific posture, since leaning back or forth on the chair could have greatly altered the actual viewing distance.

3.7 Test participants

The study was initially completed by 20 test participants, from which 13 were male and 7 were female. The test participants were typically young adults, with an average age of 23. They all wore glasses with high diopter values. There was an additional test participant who did not wear glasses, but had a vision loss above 90%.

4. RESULTS

From the 21 (20 + 1) test participants, we collected 1512 subjective ratings. In our analysis, we first focus on the ratings of the 20 test participants, and then address the ratings of the test participant with high vision loss.

Figure 2. Rating distribution for low and high resolution.

The rating distribution for low and high resolution – based on the 1440 ratings of the 20 test participants – is shown in Figure 2. Both quality settings (i.e., resolutions) received a similar distribution, with the appropriate rating shift. The average rating for the low-resolution stimuli was 5.65, while the high-resolution stimuli achieved 6.53.

First of all, such a distribution – without the rating separation for the different viewing distances – clearly confirms that the rating scale was well utilized by the test participants. The motivation for using a 10-point ACR scale instead of the 5-point scale defined by the ITU-T Rec. P.910* was to provide a greater assessment space, which enables the registering of smaller, less significant perceptual differences. The drawback of a larger scale is that the lower and upper end of the scale may become completely underutilized. The physiological reason behind such behavior is the need to reserve options on the ACR scale to express that certain test stimuli are even worse or even better than those that were already assessed. This may be applicable to a subjective study in which the test stimuli are degraded at different extents and they are presented to the test participants in randomized order. In such a case, if a test participant rates one of the stimuli to be 1, then if a subsequent stimulus is even worse than that, then the test participant cannot express this difference. In this study, the assessment task focused more on the viewing distance than the quality degradation. Therefore, the test participants could better utilize the scale, as there was no need for rating option reservation.

Another clear observation is the general rating consistency. In our previous work, there were 6 combinations of the resolution values. Hence, the perceivable differences between them were more subtle. This was separately analyzed for angular resolution and it was found that a high percentage of the subjective scores contradicted the relations with regard to objective quality (i.e., a stimulus based on a specific source content with a lower angular resolution achieved higher ratings than the corresponding one with higher angular resolution). This was applicable to both color-blind test participants and to test participants with issues related to visual acuity. In this study, we used only the lowest and the highest resolution combination from the previous work, thus, the perceivable differences between the test stimuli were less subtle. Its effect is very well reflected by Figure 2 (i.e., the two distributions are adequately separated), and therefore, rating consistency is not analyzed in this paper. Additionally, this can also be observed from the rating distributions and the average ratings at the different viewing distances.

*ITU-T Recommendation P.910: Subjective video quality assessment methods for multimedia applications

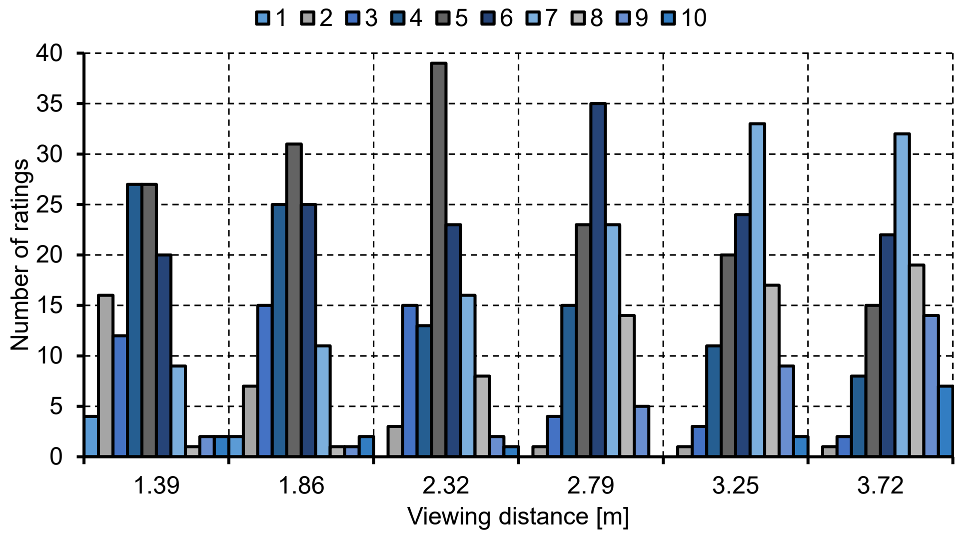

Figure 3. Rating distribution for low resolution at the different viewing distances.

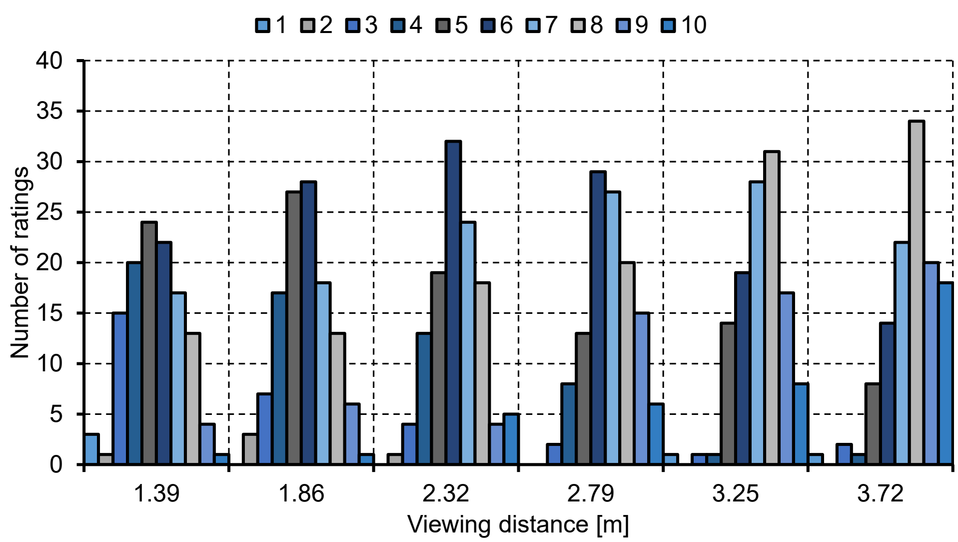

Figure 4. Rating distribution for high resolution at the different viewing distances.

The rating distribution for low and high resolution at the different viewing distances is shown in Figures 3 and 4, respectively. Each viewing distance at a given resolution was assessed by 120 ratings. For both resolutions, an evident preference can be observed towards the greater viewing distances. The closest viewing distance achieved the lowest ratings, particularly at low resolution, which received by far the highest numbers of ratings 1 and 2 (4 and 16, respectively). At the opposite end, the farthest viewing distance received the highest number of ratings 9 and 10 (20 and 18, respectively). The distributions show that the test participants were not unanimous regarding this preference, as the closest viewing distance was also rated highly by some, and the farthest viewing distance received low ratings as well. Yet, the majority had a clear preference for greater viewing distances. While rating distributions may serve the purpose of highlighting assessment tendencies among the test population, on their own, they are not sufficient to report the potential statistically significant differences between the test conditions – in this case, the different viewing distances.

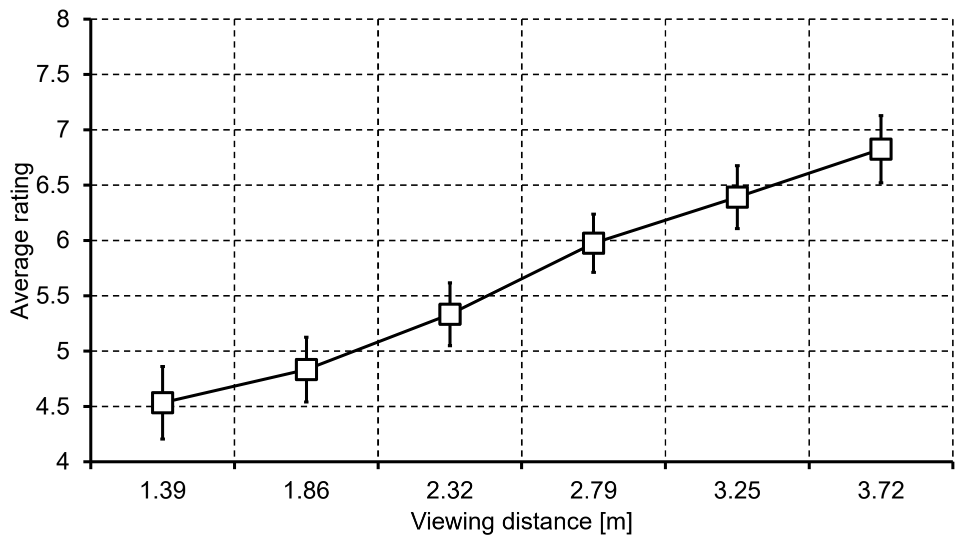

Figure 5. Average ratings for low resolution at the different viewing distances.

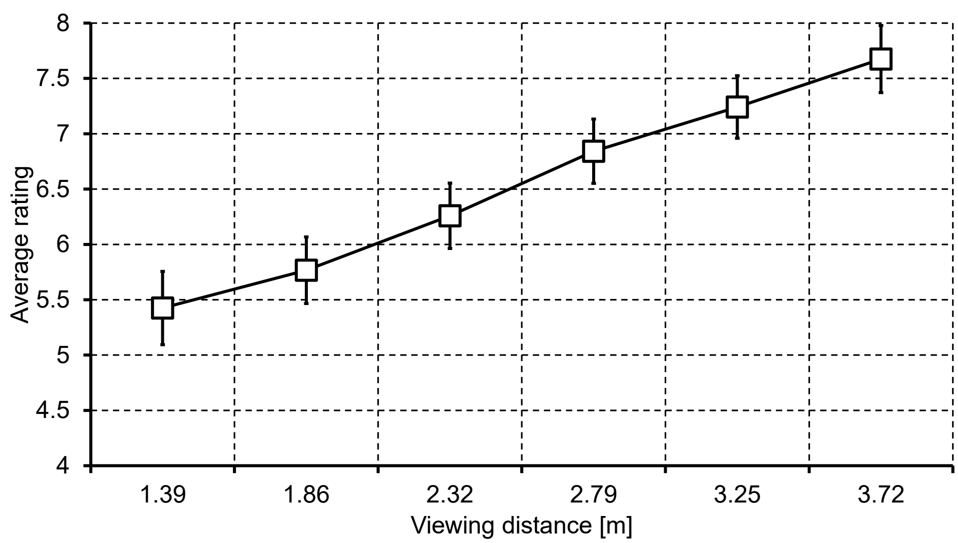

Figure 6. Average ratings for high resolution at the different viewing distances.

The average ratings for low and high resolution at the different viewing distances are shown in Figures 5 and 6, respectively. It is apparent that there are statistically significant differences between the investigated viewing distances, as the 0.95 confidence intervals do not overlap. Furthermore, there are also statistically significant differences between the two resolutions for each and every viewing distance. These findings are analogous to our previous work in terms of distance-related preference, yet this study managed to achieve statistical significance. This is primarily due to the better focus on the investigated topic on the level of experimental setup and, of course, the higher number of test participants. Indeed, according to ITU-T Rec. BT.500[†], at least 15 test participants are required for such a QoE study. While the previous work did actually include 15 test participants, they were divided into groups of 7 and 8 individuals. When analyzed in their respective groups, these test participant numbers were not sufficient to reach statistical significance. Moreover, the group of color-blind individuals in that research did not have such a clear preference towards greater distances.

[†]ITU-T Recommendation BT.500: Methodologies for the subjective assessment of the quality of television images.

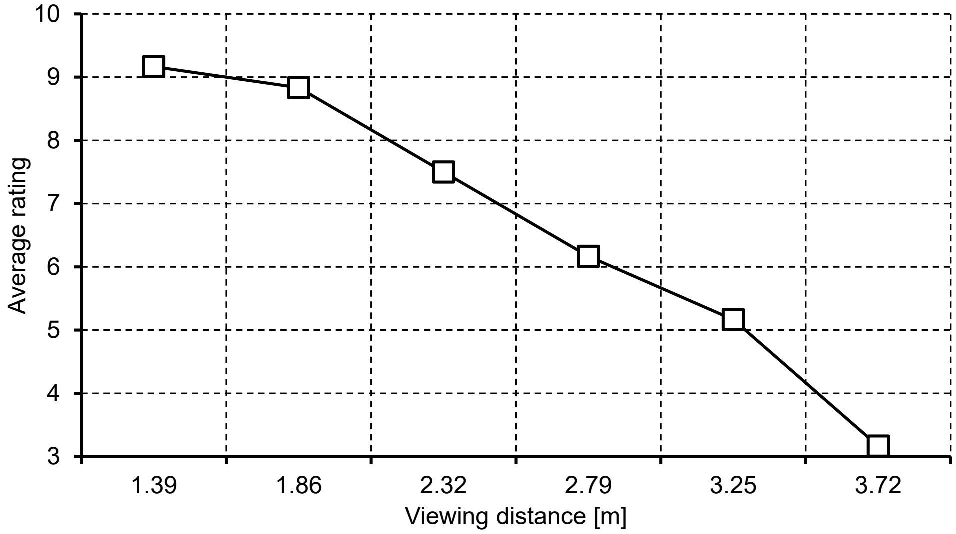

Figure 7. Average ratings of the test participant with high vision loss for low resolution at the different viewing distances.

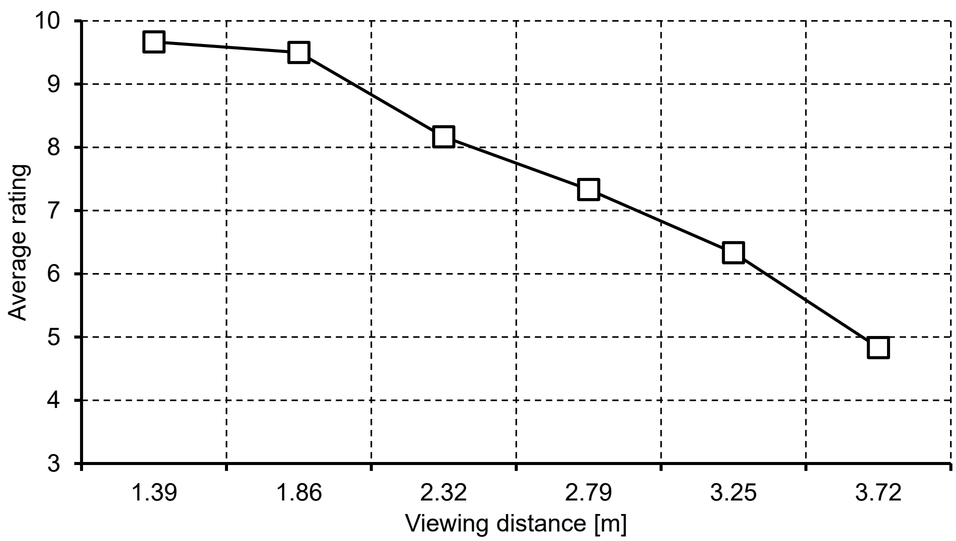

Figure 8. Average ratings of the test participant with high vision loss for high resolution at the different viewing distances.

For the 20 test participants, 18 of them preferred greater distances and only 2 favored closer ones. For the latter 2 test participants, their average rating differences were within 1, while the same values for other test participants were sometimes above 5 – of course, in the opposite rating direction. Additionally, only one of these 2 test participants had a clear preference for closer distances. The other one assessed 2.79 m with the highest scores, yet the average rating differences are even smaller.

As stated earlier, the subjective study was also completed by an individual with high vision loss (above 90%). Average ratings of this test participant for low and high resolution at the different viewing distances are shown in Figure 7 and 8, respectively. As indicated by the figures, the preference of the test participant was the opposite of the previously introduced results; closer viewing distances are clearly preferred, due to the issues related to sight. The extents of the rating differences reach and even surpass those that were measured for the 18 test participants (e.g., 8 for one of the laser-scanned statues). Moreover, the results are consistent in terms of quality.

5. CONCLUSION

In this paper, we presented our work on the viewing distance of light field visualization, as perceived and preferred by individuals with issues related to visual acuity. The investigated usage context covered the static observer model. The results indicate that greater viewing distances are preferred. The obtained data is analogous to the previous findings,[2] and shows less rating pattern diversity than the work on the subjectively-preferred viewing distance,[32] during which the test participants were screened for normal vision via the Snellen chart (visual acuity) and the Ishihara plates (color vision). The subjective study presented in this paper achieved statistically significant differences between the 1.86 m and the 3.72 m viewing distances for both low and high resolution values, where 3.72 m corresponds to the maximum recommended viewing distance, based on the angular resolution of visualization. In fact, the ratings for both of these distances are significantly different from 2.79 m for both resolutions, which further highlights the consistency in preference. The test was also completed by an individual with severe vision loss (above 90%), which resulted in an opposite preference (i.e., the closer viewing distances were preferred by the test participant).

As for future work, there are many research questions that should be addressed. First of all, viewing distance in this work and in the previous study was constrained by the theoretical limit. It should be investigated whether even greater distances (i.e., at which visualization would become more flat 2D than 3D) are preferred. The work should be extended to the different observer motion models, including sideways movement and also dynamic alterations regarding viewing distance. The effect of disadvantageous lighting conditions – including distracting external light sources – should be studied as well, since reduced visual capabilities may react differently. Finally, the topic of task performance is also of interest, since at the time of writing this paper, the correlation between the efficiency of the interaction with light field systems and the preferred viewing distance is not yet covered by the scientific literature. This latter statement is not only applicable to those with issues related to visual acuity, but such correlation has not yet been addressed in general.

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