Displays 45 (2016) 1–5

Contents lists available at ScienceDirect

Displays

journal homepage: www.elsevier.com/locate/displa

Viewers' optimization of preferred viewing distance by spatial resolution of TV display ☆

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ARTICLE INFO

Article history:
Received 14 October 2015
Received in revised form 18 July 2016
Accepted 24 July 2016
Available online 25 July 2016

Keywords:
TV viewing distance
Preferred viewing distance
Ultra-high-definition TV
8k

ABSTRACT

We have shown in a previous paper that preferred viewing distance (PVD)—a viewer's favored distance from which to watch TV in the home viewing environment—is shorter when watching a high spatial resolution 4k TV than on a high-definition TV (HDTV). PVD depends on (1) the spatial resolution of the viewer's object of interest in the relevant scene, (2) whether viewers have sufficient time to optimize their PVD, as with still images, and (3) whether they are appropriately encouraged to pay attention to the object at hand on the screen, by, for example, narrative instructions. In this paper, we demonstrate that an analogous result is obtained in a comparison between high spatial resolution 8k TV and HDTV: The PVD of viewers for 8k TV is shorter than that for HDTV. This result suggests new possibilities for high spatial resolution TV, such as novel applications and TV programs that are especially developed for 8k TV systems.

1. Introduction

The ultra-high-definition television (UHDTV) system [1,2] is designed to have a spatial resolution of 4320 scan lines × 7680 horizontal pixels, and is often referred to as an "8k system" owing to its number of horizontal pixels. Such high spatial resolution is required so that viewers do not experience image degradation or image blurring when watching an 8k UHDTV with a horizontal field-of-view (FOV) as wide as 100 deg. Viewers thus feel as though they are in the displayed space [3,4]. This sensation – often referred to as a sense of presence or "being there" – can be experienced by viewers watching TV images of sufficiently high quality.

When producing TV programs appropriate for an 8k UHDTV with high spatial resolution, camera techniques may change accordingly from traditional zoom-ins that show viewers details of an object of interest. In addition, camera orientations that retain the object within the camera frame may decrease. This decrease in camera motion may contribute to avoiding visually induced motion sickness in viewers [5]. Avoiding excessive camera movement or changes in camera orientation (i.e., panning and tilting) is desirable for reducing the risk of motion sickness. Fewer zoom-ins may also change viewer behavior, including viewers' preferred viewing distance.

In designing a TV broadcasting system, two TV viewing distances should be considered: the design viewing distance (DVD), and the preferred viewing distance (PVD).

The DVD is important for TV broadcasting system assessment, such as the subjective evaluation of image quality and the performance evaluation of audio-visual equipment used in the broadcasting studio. Therefore, it is included among the standard viewing conditions recommended by the International Telecommunication Union Radiocommunication Sector (ITU-R) [6]. In HDTV assessment, the standard DVD is three times the image height (3 H). Although the DVD for UHDTV systems has not yet been standardized, it can be defined as the distance from which viewers with a visual acuity (VA) of 1.0 cannot resolve or perceive scan lines or pixel structure on the display surface. The DVD for UHDTV is 0.75 times the image height (0.75 H). Studies on UHDTV systems based on this DVD have been conducted to determine the sense of presence [4] and visually induced motion sickness [5].

On the other hand, the PVD, which is defined as the favored viewing distance in the home viewing environment [7–9], depends on the screen size or image height. The ratio of the PVD to the image height, which is often referred to as the relative viewing distance, decreases as the image height increases. The PVD also differs between still and moving images. The above results were obtained and recommended for standard definition TV (SDTV) and HDTV [8]. However, the PVD for UHDTV has not yet been researched because such systems and their audio-visual equipment are still being developed.

☆ This paper was recommended for publication by Richard H.Y. So.

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http://dx.doi.org/10.1016/j.displa.2016.07.003
0141-9382/

Literature in this area suggests that image size and resolution have little effect on the PVD [9,10]. However, this appears to be inconsistent with ITU-R BT.1127 [11], which defines TV image quality as a function of the relative viewing distance and suggests that image resolution affects image quality and viewing distance. Furthermore, only a single PVD was determined in the studies cited above [9,10] because viewers in the relevant experiments moved to a preferred viewing position. If viewers are allowed to move freely to their preferred viewing position for each scene and object viewed (e.g., by standing), the resulting PVDs might differ from that cited in the literature. This is especially true of moving images or rapid changes of scene, which discourage viewers from changing their PVD because they do not have sufficient time to move to a preferred viewing position.

In our previous study [12], we hypothesized that viewers might adjust their PVD when watching a TV with a wide FOV and high spatial resolution, despite the inconvenience of decreasing or increasing viewing distances to see the details or gain an overview of the images, respectively. This hypothesis assumes that the behavior of a TV viewer is analogous to that of a viewer in an art museum because both may desire to view an entire image and its details simultaneously. In a previous study, we successfully verified our hypothesis by showing that the PVD decreases, when a viewer is watching a TV at a wide FOV and high spatial resolution, in a comparison between 4k and HDTV spatial resolutions [12]. We have also shown that viewers can actively adjust and optimize their PVD when sufficiently motivated (i.e., by being directed by a narration, as in this paper) and presented with still images for an adequate length of time. In our previous study, we had no choice but to compare the PVDs for a 4k system and HDTV, instead of comparing those for 8k and HDTV, because the apparatus was limited as we had no 8k display available. Because we now have an 8k display available and, generally speaking, the extrapolation of the previous 4k result to 8k spatial resolution is invalid, we conduct an experiment in this paper that is similar to that of our previous study but at extended spatial resolution, to verify our hypothesis for a comparison between the PVDs for an 8k system and HDTV and to verify the scientific reproducibility.

We conduct an experiment to compare viewer behavior, including viewing distances on an HDTV and an 8k system when watching the same TV program. We are primarily interested in the difference in PVD for these two spatial resolutions because a TV with a higher spatial resolution might enable viewers to watch from a closer distance than with a lower spatial resolution. To verify the difference in PVD, we measure its dynamic changes by giving viewers sufficient time to move to their preferred viewing position while watching lasting still images, along with a narrative that prompts them to attend to certain parts of those images. We are also interested in differences in the subjective evaluations of image quality, the degree of image detail, the degree of participants' interest in the program, as well as participant behavior. The subjective evaluations are conducted mainly to investigate the relationship between the viewing distance, the resolution, subjective image quality, and subjective image detail. Furthermore, the degree of participants' interest in the program is measured to test the effects of image resolution on viewer interest.

2. Methods

Our experiment was conducted according to the following procedure, which is almost identical to the experimental procedure used for our previous study [12]. We sought to measure the binocular visual acuity (VA) of participants after securing their informed consent. Participants were first shown an introduction to a TV program by using an HDTV liquid crystal display (LCD).

Following this, an 8k LCD was used to present a main TV program with two spatial resolutions. The program runs for approximately 420 s and consists of a series of still images (13 still images) accompanied by narration to investigate the effects of high spatial resolution. The program, called "Miracle Spaulding Collection," showed "Ukiyo-e" (color prints of everyday life in the Edo period in Japan) on an 8k LCD with an 85-in. long diagonal. The program consisted of still images without zoom-ins. The narrator prompted the participants to attend to a number of features of the images. For example, the narrator encouraged viewers to pay attention to a part of an Ukiyo-e title written in Japanese characters edged with Peruvian blue at ~80 s time points. At other time points, other topics that attracted viewers' attention and were related to displaying Ukiyo-e were offered. We down-sampled the 8k images into HDTV images using wavelet transformation [13].

Our experiment was based on a randomized, double-blind matched pairs design. Eighteen pairs of participants were matched in terms of sex, age within two years of each other, and binocular VA. A spatial resolution was assigned at random to every participant, each of whom was unaware that two spatial resolutions were used in the experiment. The experimenter was also unaware of the spatial resolution assignment, which was undertaken by a third party. Each participant watched the program once and adjusted his/her viewing distance freely. The viewing positions were recorded as a function of time. We define the viewing distance as the length of a straight line from the viewer to the display surface.

2.1. Participants

Fifty-nine healthy adults were enrolled in our experiment, 36 of whom were grouped into 18 pairs, each matched according to sex, age (within two years of each other), and binocular VA (2 male and 16 female pairs; mean age, 30.1 years for the HDTV group, and 29.9 years for the 8k group; range, 22–34; mean VA, 1.46). The participants were instructed to watch TV while standing and to freely select their viewing position by moving. The participants wore headgear with an upward-facing LED that was filmed by an overhead ceiling camera with a fish-eye lens in order to record the participants' movement. When the program started, each participant's viewing distance was 80 cm, which is 0.75 times the display height (0.75 H) and corresponds to the DVD. This short initial viewing distance was chosen based on the result of a preliminary experiment, which showed that an ordinary initial viewing distance, such as 3 H, tends to prevent participants from approaching the display and noticing the high spatial resolution that would enable them to watch the TV at a shorter distance. After starting at an initial viewing distance of 0.75 H, most participants freely selected their viewing distance.

2.2. Subjective evaluation

Subjective evaluations of image quality, image detail, and participants' interest were conducted after the participants had watched the program. The participants recorded their ratings on three 10-cm visual analogue scales (VAS) [14,15] for perceived image quality, the degree of image detail, and the degree to which the program aroused their interest. The entire subjective assessment was conducted in conformity with the recommendations of the ITU-R [6,8], with the exception of our assessment of viewing distance. Accordingly, the screen illumination was approximately 30 lx with a D65 background. The distance from the floor to the center of the LCD monitor was 135 cm. The participants were all non-experts.

2.3. Apparatus

The 8k LCD [16] had a spatial resolution of 4320 scan lines by 7680 horizontal pixels. The area of the room was 6.5 m by 11.5 m. The LCD was positioned at one end of a room along its shorter wall.

Still images were played with eight synchronized video disk recorders (Keisoku-giken UDR-2E), and narration was played on a PC using a loudspeaker (Fostex 6301B). Images from the ceiling camera, which contained the participants' viewing positions, were taken using a Hitachi ip-5000 image processing board to convert the fish-eye coordinates into rectangular coordinates. The data recorded on viewing positions included the distance between the LCD surface and a light-emitting diode (LED) on the headgear. One pixel of the ceiling camera corresponded to a maximum distance of 4 cm.

2.4. Data analysis

The average viewing distance was calculated for each participant as a function of time. Averaged and paired data for the 8k and HDTV groups were analyzed by a paired *t*-test, and Cohen's d was calculated for the effect size.

To investigate the temporal aspect of the viewing distances for the 8k and HDTV resolutions, a cross-correlation analysis was performed between the two time-varying viewing distance curves.

Visual Analog Scale (VAS) ratings were measured with a ruler to obtain the distances from the origin, and the distance data were analyzed by a paired *t*-test to verify the rating differences between the two spatial resolutions.

3. Results

The viewing distances of participants who watched the 420 s TV program were shorter for the 8k group than for the HDTV group (Fig. 1). The difference in viewing distance between the 8k group and the HDTV group ranged from 0 to 97 cm, and the two time-varying viewing distance curves were similar except for the mean value of the waveform (or the direct current (DC) offset). A paired *t*-test showed that the viewing distance for the 8k spatial resolution (M = 132.51, 1.25 H, SD = 53.17) was significantly shorter than that for the HDTV spatial resolution (M = 183.71, 1.74 H, SD = 56.68, t(17) = −2.663, P = 0.016, Cohen's d = 0.93). This result indicates that spatial resolution is an important factor that affects viewing distance. To conduct a temporal cross-correlation analysis of viewing distances for the two spatial resolutions, we subtracted the DC level from the two time-varying curves of the viewing distance, and calculated the cross-correlation coefficient and lag time. The lag time was zero, while the cross-correlation coefficient was 0.711. This strong cross-correlation indicates that the viewing distances for the 8k and HDTV spatial resolutions changed in parallel, and that the content of the program at each time point was an important factor affecting viewing distance.

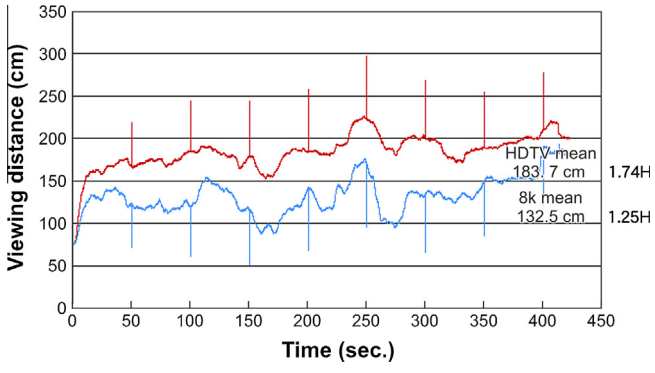

Fig. 1. Averaged viewing distances for participants (n = 18) viewing a 420-s TV program in 8k and HDTV spatial resolutions. Error bars were added every 50 s to show the standard deviations. The viewing distance of the 8k resolution (M = 132.51, 1.25 H, SD = 53.17) was significantly shorter than that of the HDTV resolution (M = 183.71, 1.74 H, SD = 56.68, t(17) = −2.663, P = 0.016, Cohen's d = 0.93). The temporal cross-correlation of the viewing distances for 8k and HDTV resolution was 0.711. The two curves on the figure show local dips at the same periods in the program (i.e., at approximately 80, 170, and 320 s), representing viewers' approaches to the LCD.

Three paired t-tests were conducted to assess differences in the subjective evaluation of image quality, image detail, and degree of interest aroused by the program between the two spatial resolutions (Table 1). The results showed that the subjective evaluation of the image quality of the 8k resolution (M = 75.06, SD = 18.62) was not significantly different from that of the HDTV resolution (M = 69.56, SD = 17.61, t(17) = 0.882, P = 0.390, Cohen's d = 0.30). The results also showed that the subjective evaluation of the image detail of the 8k resolution (M = 81.94, SD = 15.94) was not significantly different from that of the HDTV resolution (M = 71.89, SD = 21.93, t(17) = 1.430, P = 0.171, Cohen's d = 0.53). Taking the results of the viewing distance into consideration, these results suggested that the participants avoided the degradation of image quality by controlling their viewing distances (i.e., longer viewing distances for the HDTV resolution than for the 8k resolution to avoid image blur). The shorter viewing distances for the 8k resolution in turn enabled the participants to perceive more detail in the images.

The results also showed that the subjective evaluation of the degree of interest generated by the same program played on the 8k resolution (M = 85.06, SD = 9.86) was significantly different from that played on HDTV resolution (M = 74.22, SD = 18.47, t(18) = 2.172, P = 0.044, Cohen's d = 0.73). This result suggested that a high spatial resolution TV can generate greater viewer interest than a low spatial resolution TV, even if the same program is played.

Table 1
Results of the subjective evaluations.

	8k		HDTV	
	Mean	SD	Mean	SD
Quality	75.06	18.62	69.56	17.61
Detail	81.94	15.94	71.89	21.93
Interest	85.06	9.86	74.22	18.47

Fig. 2. Image shown at approximately 170 s into the program and a magnified image of the region to which attention was directed. The participants were prompted to pay attention to the receding hairline of the woman.

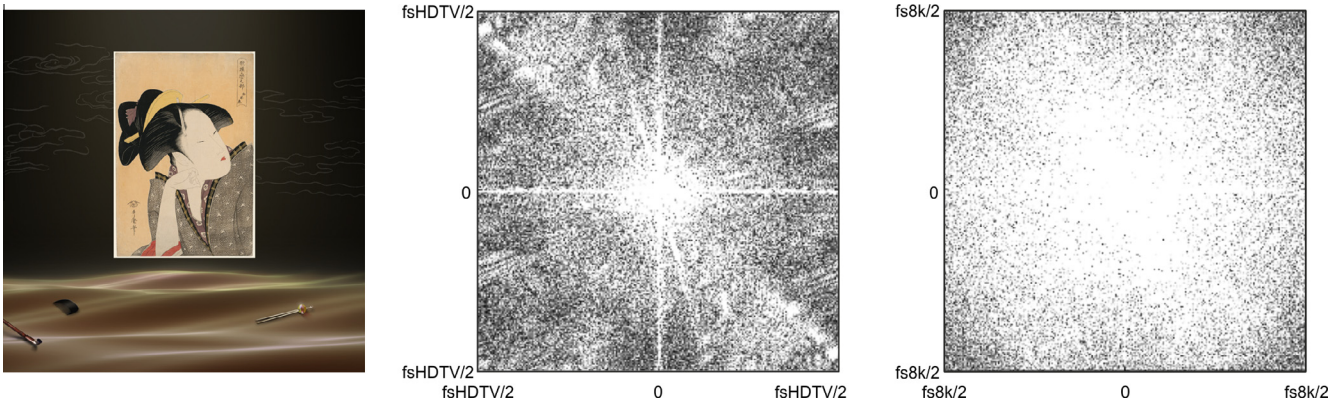

Fig. 3. Two-dimensional DFT (Discrete Fourier transformation). The left panel shows the analyzed area (4096 × 4096 pixels in 8k image) of Fig. 2. The center panel shows the power spectrum of the HDTV image and the right panel shows that of the 8k resolution. "FsHDTV" and "fs8k" indicate the sampling frequency of each image for the corresponding resolution. The 8k image had a richer power spectrum in high spatial frequency than HDTV.

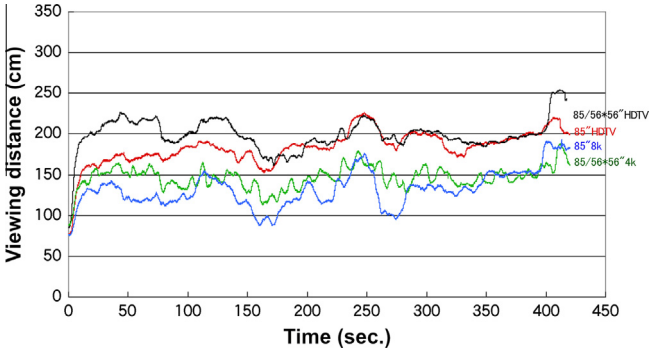

Fig. 4. Comparison between the present experiment PVDs and the previous experiment PVDs. The blue and red curves indicate the present PVDs for an 85 in. 8k and HDTV display, respectively. They are identical with Fig. 1. The black and green curves indicate the 85/56 times previous PVDs for 56 in. 4k and HDTV display, respectively. Although the display size differed between the two experiments, the 85/56 times PVD for a 56″ HDTV display (black) and the PVD for an 85″ HDTV display (red) are comparatively consistent, which could be anchor data to compare the 85/56 times PVD for a 56″ 4k display (green) and the PVD for an 85″ 8k display (blue).

4. Discussion

We found a significant difference in mean viewing distances between the two spatial resolutions (8k and HDTV), and the viewing distances for each changed in parallel across time. We also compared the shortest and longest viewing distances between the two spatial resolutions. To avoid the effect of the initial viewing distance, the shortest and longest viewing distances were determined for each participant (in the 30–400 s period). Although the shortest viewing distance for the 8k resolution ($M = 59.57$, $SD = 57.87$) was not significantly shorter than that for the HDTV resolution ($M = 100.83$, $SD = 55.48$; paired t-test, $t(17) = -2.00$, $P = 0.061$, Cohen's $d = 0.73$), a moderate effect size was found that showed a tendency toward a shorter viewing distance for high spatial resolution TV than for low spatial resolution TV. The long viewing distance for the 8k resolution ($M = 213.63$, $SD = 70.24$) was not significantly different from that of the HDTV resolution ($M = 235.42$, $SD = 69.33$; paired t-test, $t(17) = -1.188$, $P = 0.251$, Cohen's $d = 0.31$). This shows that higher spatial resolution prompted viewers to watch the LCD at a shorter viewing distance. Taking the results of the subjective evaluation into consideration, we observe that participants can avoid the degradation of image quality by controlling their viewing distances to perceive the details of images presented on the LCD at a high spatial resolution.

The curves in Fig. 1 show a number of local dips at the same time points during the program (i.e., at approximately 80 s, 170 s, and 320 s), representing viewers' temporary approaches toward the LCD. At the ~80 s time point, a narration prompted the participants to pay close attention to Japanese characters. Subsequently, at the ~170 s time point, the narrator described sophisticated techniques used to print the receding hairline of a woman (Fig. 2). At the ~320 s time point, the participants were prompted to answer a quiz to find three differences between two versions of an Ukiyo-e print. The spatial frequencies of the Japanese characters, the receding hairline, and the details of the prints were high, and viewers needed to approach the LCD to view the details. Fig. 3 shows two-dimensional Discrete Fourier transformations (DFTs) corresponding to Fig. 2. The power spectrum of each image shows that the 8k image had a richer power spectrum in high spatial frequency than the HDTV image. This suggests that viewing distance was related to the spatial frequency of the subject of focus presented on the TV monitor.

The curves in Fig. 1 also show two obvious local peaks at the same time points during the program (i.e., at approximately 250 s and 400 s), representing the viewers' long viewing distances. At the ~250 s time point, Van Gogh's oil painting "The bridge in the rain" was presented at near full height, and occupied a third of the width of the LCD. At the ~400 s time point, a number of ukiyo-e were shown scattered on the LCD. The increase in viewing distance here suggests that viewers decided to step back from the LCD in order to be able to view the entire oil painting, or all ukiyo-e.

Our previous experiment [12], which compared the PVDs between 4k and HDTV, was conducted using two LCDs with a diagonal length of 56 in. To compare the previous PVDs for two 56-in. displays with the present PVD for an 85-in. display, we multiplied the previous PVD data by 85/56. Fig. 4shows the multiplied PVDs for two 56-in. displays with a drop-frame correction in the time-code and the present PVD for an 85-in. display. The uppermost black curve shows the multiplied PVD for HDTV images presented on a 56 in. display, and the following red curve, which overlaps with the latter half of the uppermost black curve, shows the present PVD for HDTV images presented on an 85 in. display. The first half of the red curve, which shows multiplied PVD for HDTV images presented on an 85-in. display, has a shorter PVD than the black curve, which represents the multiplied PVD for HDTV images presented on a 56-in. display. This is consistent with the short relative viewing distance when viewing large displays compared with small displays [9,10]. The two overlapping PVD curves for HDTV images can be used as anchor data for comparison between the other two PVD curves, i.e., the green curve, which

shows multiplied PVD for 4k images presented on a 56 in. display, and the blue curve, which shows the present PVD for 8k images presented on an 85 in. display. The green curve of multiplied PVD for 4k images presented on a 56 in. display shows a longer PVD than the blue curve of present PVD for 8k images presented on an 85 in. display, apart from the final section after 350 s. The difference in PVDs indicates that the higher the image resolution became, the shorter the PVD became. We speculate that the participants were able to optimize their PVD according not only to the display size but also to the image resolution, in other words, according to the degree of image blur or degradation of image quality.

5. Conclusion

In this paper, we have described an experiment to compare viewer behavior, particularly their PVD, while watching the same TV program on an 8k system and on an HDTV. The results show that the spatial resolution of the objects of interest affect viewing distance (i.e., viewing distance decreases when TV images are presented at a higher spatial resolution). They also show that participants can actively adjust and optimize their viewing distances when they are sufficiently motivated (e.g., by the narration in our experiment), and are presented with images for an adequate length of time.

The results of our experiment verified our hypothesis that viewers tend to adjust their PVD when watching a TV with a wide FOV and high spatial resolution, despite the inconvenience of decreasing or increasing viewing distances to see the details or an overview of the images, respectively. We compared participants' viewing distances for 8k and HDTV resolutions and detected a significant decrease in viewing distances for the 8k resolution compared with the HDTV resolution. We concluded that a higher spatial resolution TV can arouse greater viewer interest than lower spatial resolution TV. In conjunction with the results of the comparison in PVD between 4k and HDTV in our previous paper [12], our results here confirm that viewers shorten their PVD when viewing high spatial resolution TV to see more detail in the images. This result suggests new possibilities for high spatial resolution TV, such as novel methods of use and new TV programs that are produced especially for 8k TV systems.

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