

Tested Perceptual Difference Between UHD-1/4K and UHD-2/8K

By Michael D. Smith, Michael Zink, and Aansh Malik

Abstract

The screen size and the resolution of the displays available to the consumer market have been steadily increasing. According to established vision science, there are limits to the human visual system for the perceptibility of resolution at typical viewing distances. This paper discusses a subjective evaluation that was performed to assess the perceptual difference between UHD-1/4K and UHD-2/8K for various types of content on an UHD-2/8K consumer display. It also performs a detailed frequency and visibility analysis of the content to determine the characteristics of the most perceptual content and establishes a relationship between the subjective test results and the vision science.

Keywords

UHD-2/8K, high dynamic range (HDR), perceptual testing, spatial frequency, ultrahigh-definition (UHD), viewing test, visibility

EDITOR'S NOTE: *The SMPTE recognized nomenclature for 4K and 8K video formats is UHD-1 and UHD-2, respectively.*

Introduction

Over the past several years, one common trend in the consumer electronics market has been the consumer preference for larger screen sizes. Each year, the average screen size of consumer displays being sold has been increasing steadily. In line with that, display manufacturers have recently introduced 8K resolution displays into the market. This raised the question of what the impact of higher resolution screens with larger screen sizes is on the user experience. In other words, is the

increase of resolution from 4K to 8K perceptible on 8K consumer displays at typical viewing distances?

This paper attempts to answer this question by performing an assessment of the perceptual difference between 4K and 8K for various types of content on an 8K consumer display. We will start by providing an overview of the testing procedure and the test equipment used during this subjective evaluation, followed by a review of the vision science aspects to highlight how visual acuity relates to pixel density and viewing distances. We will then take a closer look at the content that was selected as part of this image assessment and review the results of the perceptual testing. This will lead to a more detailed frequency and visibility analysis of the test content to highlight some characteristics of the best performing clips from our assessment, before closing with some conclusions.

Perceptual Testing Overview

In November 2019, Warner Bros. in collaboration with the American Society of Cinematographers (ASC), Amazon Prime Video, Pixar Animation Studios, and LG Electronics, performed a subjective evaluation of high-resolution content (4K and 8K) on an 88-in. 8K display device. In total, 139 individuals participated in the evaluation—approximately two-thirds of the participants were from Warner Bros. and one-third of the

participants consisted of industry experts (e.g., members of the ASC).

Test Procedure

A maximum of five people participated in each evaluation session. To optimize the viewing angle, two participants were seated in the front row and three participants were

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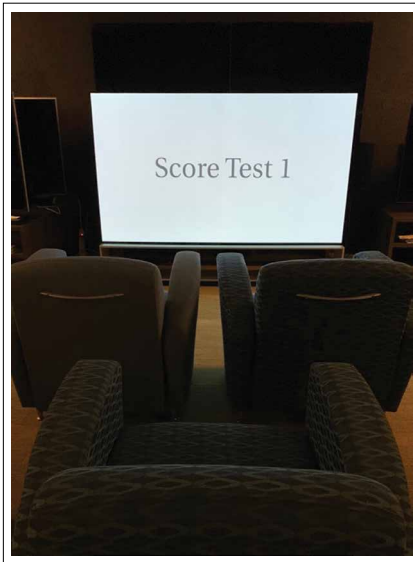


FIGURE 1. Photograph of evaluation room.

seated in the back row. According to the International Telecommunication Union Radiocommunication (ITU-R) BT.2246-6,¹ the average viewing distance in consumers' homes is 7 ft. from the screen. Based on the display screen size (88 in.), this distance is about two screen heights. Since we had two rows of seats, the front row was positioned at 5 ft., and the back row at 9 ft. from the screen. On the scoring sheet for each participant, the seating position was noted to keep track of potential differences in scores between the front and back rows. Additionally, prior to testing, a visual acuity test using a Snellen eye chart was performed on each participant, and the results were noted on the scoring sheet to determine potential differences in the results.

Figure 1 shows a photograph of the evaluation room.

The evaluation contained a variety of content from different sources, including:

- Two clips from a film-based feature film (*Dunkirk*)
- Two clips from animation features (*Brave* and *A Bug's Life*)
- Three clips from digital cameras (*Tick* and *Nature* footage provided by Stacey Spears).

All sources were original 8K material, from which a 4K version was created for comparison. All content were played back in an uncompressed format. The test itself was designed as a so-called *double-blind* test, which meant that the person evaluating the content and the person on

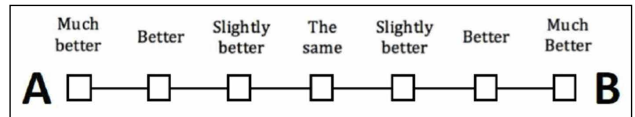


FIGURE 2. Scoring entry form.

the playback device had no knowledge about the images that were being displayed. Each clip was 10 sec in duration, with each sequence consisting of two versions of the same clip, presented twice, in the following order: Version A/Version B/Version A/Version B/Scoring.

Each clip sequence was presented three times in different orders, presented randomly:

- 8K (Version A) versus 4K (Version B)
- 4K (Version A) versus 8K (Version B)
- 4K (Version A) versus 4K (Version B).

At the end of each sequence, the participants had to rate their preference between Versions A and B on a seven-point scale, using a scoring entry form like the one shown in **Fig. 2**.

Test Equipment

The display used for the evaluation was an LG 88Z9 88-in. 8K organic light-emitting diode (OLED) television (TV). The connections and conversions used for the evaluation are shown in **Fig. 3**.

A Windows 10 PC running Black Magic Resolve 16 software was used for content playback with the Black Magic 8K Pro video interface [quad serial digital interface (SDI)]. The Black Magic Resolve 16 software was configured with a 7680 × 4320 8K ultrahigh-definition (UHD) timeline resolution with a 23.976 frames/sec playback frame rate. The Resolve software's video monitoring was configured to use 8K UHD 4320p 23.976, with 10-bit 4:4:4 SDI with video data levels, and with the SDI configuration set to the quad link.

The four 12G SDI outputs from the 8K Pro video interface card were each connected to an AJA 12G SDI to a high-definition multimedia interface (HDMI) 2.0 converter. The first converter was configured to set the HDMI Info Frame metadata to indicate the ST 2084 perceptual quantizer electro-optical transfer function (PQEOTF) with P3D65 mastering display metadata, with min/max luminance fields set to 0.0005 and 1000 nits, respectively. The high dynamic range (HDR) static metadata fields MaxCLL and MaxFALL were set to 1000 and 400 nits, respectively. The colorimetry field was set to BT.2020 nonconstant

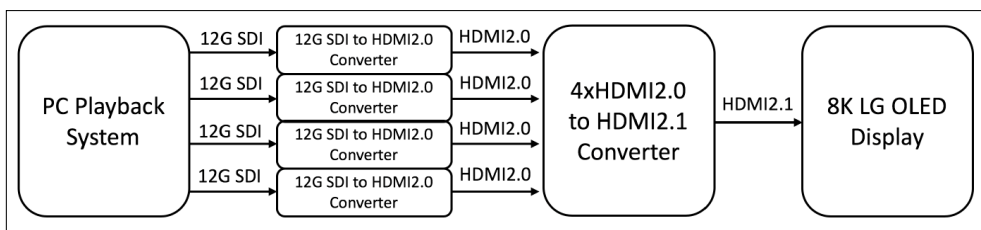


FIGURE 3. Connection and conversions for playback.

luminance. The four HDMI 2.0 outputs from the four AJA converters were connected to an ASTRODESIGN quad HDMI 2.0 to HDMI 2.1 converter. An HDMI 2.1 cable connected the ASTRODESIGN HDMI 2.1 output to the 8K LG OLED display.

A Windows 10 PC was configured with an Intel 18-core i9 central processing unit (CPU), 64 GB random access memory (RAM), 8TB SSD RAID card, and a Nvidia GTX 1080Ti graphics processing unit (GPU). The content was played back from BT.2100 PQ 7680 × 4320/23.976p 10-bit DPX files, which required a 3000 MB/s sustained file read rate.

Vision Science Review

Background

The highest frequency that a normal viewer can see is dependent on the density of cones in the fovea and the optics of the eye, and there is a consensus that these factors result in 60 cycles per degree (cpd) being the upper limit of normal visual acuity. For example, Section 5.3.1 of Howard² explains that the optics of the eye are limited to 60 cpd. This limit is also used in McCarthy³ as “Simple Acuity,” which is described as “a theoretical optical limit that can only be achieved by the keenest of eyes under exceptional viewing conditions.”

Most people are familiar with the Snellen eye chart that is shown by an optometrist to check vision. Having so-called “20/20 Vision” corresponds to the ability to read the letters on the “20/20” line, in which the viewing configuration presents the letter width/height as 5 min of arc, or 5/60 of a degree.^{4,5} The type used in the eye chart is designed so that the letters fit on a 5 × 5 grid, where the black lines and white spaces that make up the shapes of the letters have a visual angle of 1 min of arc or 1/60 degree on the 20/20 line. This means that the visual angle of one cycle (black to white transition) on the 20/20 line consumes 2 min of arc or 2/60 degrees, which corresponds to a maximum visual frequency of 30 cpd, as illustrated in **Fig. 4**.

The 20/15 and 20/10 lines of letters are below the 20/20 line of letters. The 20/10 line has letters that are twice as small as the letters on the 20/20 line, and thus the 20/10 letters have twice the maximum visual frequency of 60 cpd. A common misunderstanding is that the “20/20 Vision” describes the limits of human vision. This misunderstanding is discussed in Ref. 6 as “... contrary to popular belief, 20/20 is not actually normal or average, let alone perfect, acuity. Snellen ... established it is a reference standard. Normal acuity in healthy adults is one or two lines better. Average acuity in a population sample does not drop to the 20/20 level until age 60 or 70. This explains the existence of the two lines smaller than 20/20: 20/15 and 20/10.” In summary, “20/10 Vision” (60 cpd) is the actual limit of human vision not “20/20 Vision” (30 cpd). Details at frequencies higher than 60 cpd will not be visible to a viewer unless the visual stimulus presented falls in a special case called

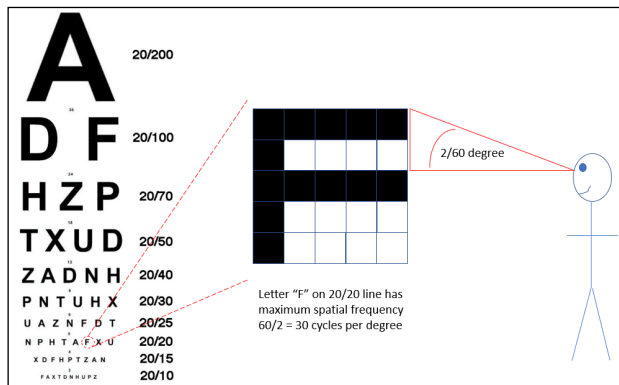


FIGURE 4. Illustration of the visual frequency corresponding to 20/20.

hyperacuity, which is the ability to discriminate line offsets and differences in the spacing of lines that are greater than 60 cpd. Hyperacuity is not considered in this paper.

Tying Visual Acuity to Pixel Density

The geometry of the viewing conditions together with vision performance determines whether the details above 4K resolution can be visible. These aspects are examined further in this section. Whether or not the content contains detail beyond 4K resolution is also discussed in a later section.

Spatial frequency units of cpd normalize the physical viewing distance and physical size of the visual stimulus being displayed to a viewer; only the angle (in degrees) is relevant in this unit. A cycle is a unit of spatial frequency detail; for example, a white pixel horizontally adjacent to a black pixel is a single spatial frequency cycle and consumes a total of two pixels, and it is the highest spatial frequency representable in a typical digital image. A lower frequency of two white pixels horizontally adjacent to two black pixels, consuming a total of four horizontal pixels, is an example of a lower frequency that can be represented in a digital image. Both examples are shown in **Fig. 5**.

The display used for the evaluation was an 88-in. 16:9 screen, with 88-in. diagonal, 76-in. screen width, and 43-in. screen height. The viewing positions were at two different distances: the front row seats were 5 ft. from the screen (60-in./43-in. = 1.4 screen heights) and the back row seats were 9 ft. from the screen (108-in./43-in. = 2.5 screen heights).

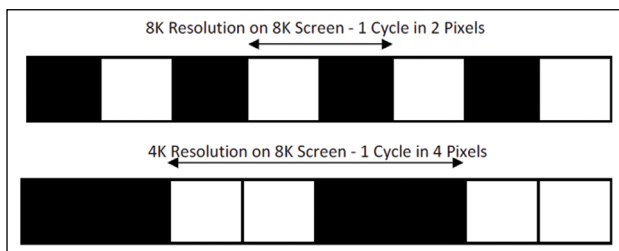


FIGURE 5. Illustration of correspondence between pixels and cycles.

The angular pixel density corresponding to each viewing position was calculated using trigonometry in units of pixels per degree as per the following equation:

$$\text{pixel density} = \frac{1}{\arctan\left(\frac{1}{V_s R_h}\right)}$$

where V_s is the viewing distance in screen heights and R_h is the vertical resolution of the screen in pixels. Using values of $R_h = 4320$ and $V_s = 1.4$ and 2.5 , respectively, leads to the calculated pixel densities of approximately 100 and 190 pixels/degree for the front and back rows. If we assume that a spatial frequency representing 4K and 8K resolutions on the screen requires four and two pixels per cycle, respectively, then the front row viewers would experience 4K and 8K resolutions as 25 and 50 cpd, respectively, and the back row viewers would experience 4K and 8K resolutions as 47.5 and 95 cpd, respectively.

As discussed in the previous section, the limits of vision performance rating (i.e., “20/20,” “20/15,” “20/10,” etc.) are related to the highest spatial frequency that can be perceived, which can be compared with the spatial frequency of 4K/8K resolution shown in a viewing geometry to determine if a viewer will be able to see the respective resolution. **Table 1** summarizes this comparison.

In **Table 1**, 1.0 means only 4K resolution is visible, whereas 2.0 means 8K resolution is visible.

Viewers with “20/10 Vision” in the front row can see 8K resolution because the ratio 2.4 is greater than 2.0, and in the back row, they can see 4K resolution because the ratio 1.3 is greater than 1.0. Viewers with 20/20 or better vision in the front row can see higher than 4K resolution.

Viewing Distance Assumptions

The industry has used the limit of “20/20 Vision” to derive its optimal viewing distance guidelines in the widely referenced ITU-R BT.2246 “The present state of ultra-high-definition television,”¹ see, for example, BT.2246-6

TABLE 1. Vision performance and visual frequency threshold.

| Vision performance | Visual frequency threshold (cpd) | Visual frequency threshold/4K resolution visual frequency | |
|--------------------|----------------------------------|---|----------|
| | | Front row | Back row |
| 20/20 | 30 | 1.2 | 0.6 |
| 20/15 | 45 | 1.8 | 0.9 |
| 20/10 | 60 | 2.4 | 1.3 |

TABLE 2. Optimal viewing distance according to ITU-R BT.2246-6.

| Image system | Optimal horizontal viewing angle | Optimal viewing distance |
|--------------|----------------------------------|--------------------------|
| 1920 × 1080 | 32° | 3.1 H |
| 3840 × 2160 | 58° | 1.5 H |
| 7680 × 4320 | 96° | 0.75 H |

Section 2.5.2: “The ‘design viewing distance’ gives the angular resolution (pixel/unit visual angle). It has tacitly been taken to be one pixel/arc-minute.” As discussed previously, arranging the viewing conditions such that there is one pixel per 1/60 degree results in the highest spatial frequency of the imaging system being 30 cpd. The industry viewing distance guidelines from BT.2246-6 are duplicated in **Table 2**, where H represents the screen height units.

The ITU-R BT.1845-1⁷ standard provides an equation for deriving the optimal viewing distance and optimal viewing angle using a target pixel density of one pixel per 1/60 degree, given a vertical resolution parameter (i.e., 1080) and aspect ratio parameter (i.e., 16:9). The Carlton Bale website⁸, which is commonly referenced in papers and blogs about viewing distance and resolution uses a target pixel density of one pixel per 1/60 degree in its viewing distance design criteria. A recent study⁹ about the visibility

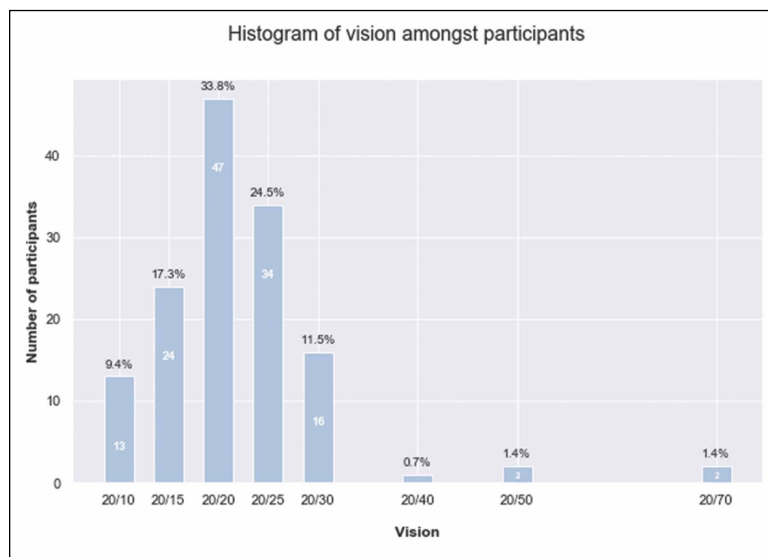


FIGURE 6. Histogram of participant’s vision performance.

of 8K detail in motion pictures also used an upper limit of 60 pixels/degree.

Visual Acuity of Test Participants

Before performing the viewing test, the vision performance of each viewer was recorded on their score sheet. Twenty-seven percent of the viewers had better than “20/20 Vision,” 34% had “20/20 Vision,” and 39% had worse than “20/20 Vision.” A histogram of the vision performance of the viewers is shown in **Fig. 6**.

Content Analysis

Content Selection and Preparation

Native 8K HDR content was delivered from different titles in various file formats such as tagged image format file (TIFF), digital picture exchange (DPX), and extended dynamic range (EXR). The content was carefully reviewed, and seven clips were selected, of 10-sec duration each. The camera in the selected clips used either slow dolly movement or was fixed, which minimized motion blur due to camera movement. The scene objects in the selected clips were not moving fast, which minimized motion blur due to object motion. The native 8K HDR content for the selected clips was saved as 10-bit DPX files for playback purposes.

Thumbnails from the selected clips are shown in **Table 3** and were converted from HDR to standard dynamic range (SDR) only for inclusion in this paper.

A 4K HDR version of each clip was derived from the native 8K HDR version using a multistep process with Foundry’s NUKE software. The 8K HDR image data were linearized by applying the PQ EOTF and then resized to 4K using a cubic filter. The PQ inverse-EOTF was then applied to the 4K image data, and the 4K PQ image data was resized back to 8K using a cubic filter and saved to 10-bit DPX files. The reason for resizing the 4K HDR version back to 8K was to consistently operate the display with only 8K sized input, which prevented

the display from renegotiating the HDMI connection when the source content resolution changed from 4K to 8K and vice versa. This ensured that no external factors, such as on-screen messages due to HDMI renegotiation, informed the viewer of the resolution being displayed.

HDR Statistics

The selected content was purposely a mix of both bright and dark scenes. The HDR10 content metadata, MaxCLL and MaxFALL, were calculated for each clip and are shown in **Table 4**.

Test Results

Averaged Results

Across all 139 participants, on average, 8K was rated marginally “Slightly Better” than 4K. The averaged results with confidence intervals are shown in **Fig. 7**. Since the confidence intervals overlap, no conclusion can be made about differences between clips.








Better Vision = Better Results

Across the participants with the vision performance of 20/20 or better, on average, 8K was still rated marginally “Slightly Better” than 4K, although for some clips, the mean score improved about 50%, it was still closer to 0 (Same) than 1 (Slightly Better). The averaged results with confidence intervals are shown in **Fig. 8**.

TABLE 4. HDR10 content metadata for the selected clips.

| Clip number | Clip description | MaxFALL | MaxCLL |
|-------------|------------------|---------|--------|
| 1 | Dunkirk—Close | 160 | 490 |
| 2 | Dunkirk—Wide | 226 | 445 |
| 3 | Brave | 1.5 | 103 |
| 4 | A Bug’s Life | 94 | 375 |
| 5 | Tick—Cave | 4.2 | 1016 |
| 6 | Tick—Spaceship | 18 | 1000 |
| 7 | Nature | 372 | 3000 |

TABLE 3. Example frames from the selected clips.

| Dunkirk | Tick | Brave/A Bug’s Life | Nature (Stacey Spears) |
|---|---|--|---|
|  |  |  |  |
|  |  |  | |
| 8K Film Scans | 8K RED Digital Camera | 8K Animation | 8K RED Digital Camera |

Across the participants with excellent “20/10 Vision” performance sitting in the front row, on average, 8K was rated “Slightly Better” than 4K for two of the seven clips (Clips 4 and 7). The averaged results with confidence intervals are shown in **Fig. 9**.

Frequency and Visibility Analysis

The clear difference in scores for Clips 4 and 7 for the participants with “20/10 Vision” sitting in the front row caused us to consider if a content analysis of the clips could be used to predict the visibility differences of the different clips using only image analysis.

We started our investigation by performing a frequency analysis of the content using the Fast Fourier

Transform (FFT), like the analysis described in Katsavounidis.¹⁰ After reviewing the outputs of this analysis, we determined that such a spectrum analysis was useful for determining the presence of high frequencies in the image data but did not provide any information about the visibility of said high frequencies.

We developed the simple algorithm described in **Table 5** to perform a high frequency detail visibility content analysis of individual frames from the selected clips.

The algorithm in **Table 5** was run on a single frame from each clip, and a cropped portion of the resulting output of the just noticeable difference (JND) images, with zero JNDs mapped to black and five JNDs mapped to white, is shown in **Table 6** for Clips 1, 4, and 7, illustrating the difference in visibility among the various clips.



FIGURE 7. Average of all scores.



FIGURE 8. Average of scores for viewers with 20/20 or better vision performance.

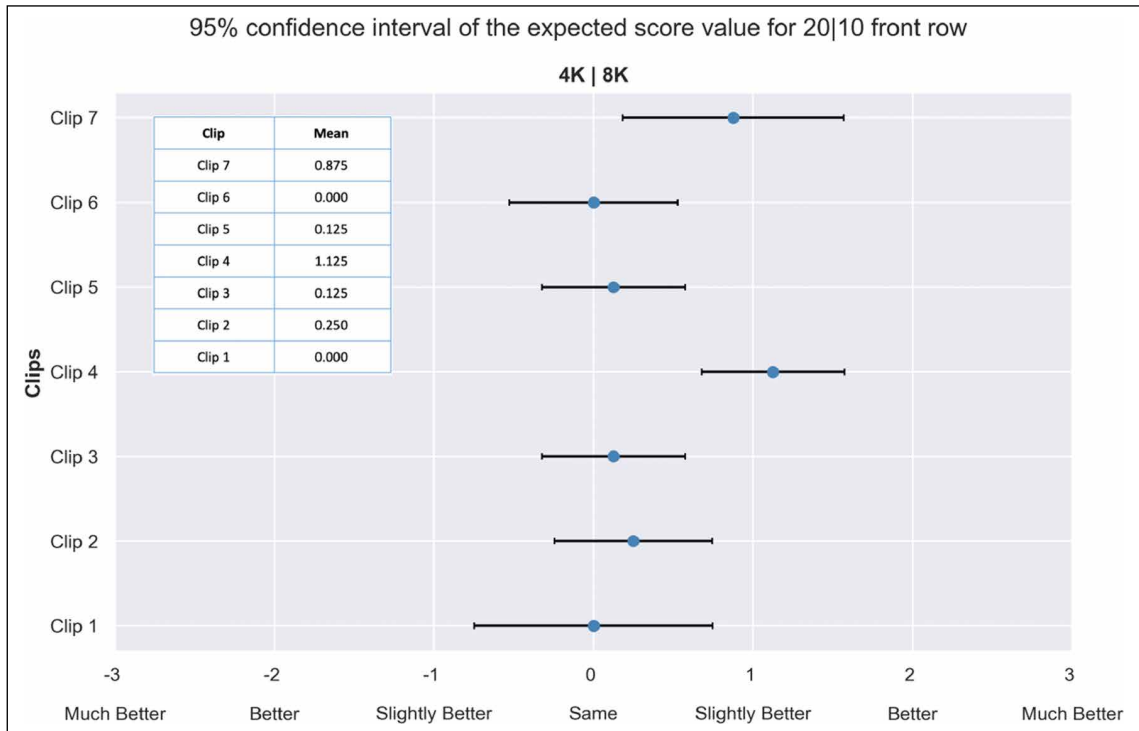


FIGURE 9. Average of scores for viewers with “20/10 Vision” performance in the front row.

TABLE 5. Algorithm for high frequency detail visibility content analysis.

Visibility of High Frequency Detail Content Analysis Algorithm

1. Convert 8K BT.2100 HDR PQ image into an 8K luminance-only image.
2. Convert 4K upres to 8K BT.2100 HDR PQ image into 4K upres to 8K luminance-only image. This is called the *LOW* image.
3. Compute the difference image between the 8K luminance-only image and the 4K upres to 8K luminance-only image. Since the difference image data will have both positive and negative values, take the absolute value of the difference image data. This represents the magnitude of the 4K–8K luminance detail. This is called the *DETAIL_MAGNITUDE* image.
4. For each pixel location (x,y):
 - A. Using the *LOW* image data, compute the modulation threshold for visual detection, using the Barten Contrast Sensitivity Model¹¹ parameterized with Luminance *L* and spatial frequency *u*, using $L = \text{LOW}(x, y)$ and $u = 37.5$ cpd. Note that in the viewing tests, the front row viewers experienced the 4K pixel detail at 25 cpd and the 8K pixel detail at 50 cpd. 37.5 cpd is the average of 25 and 50
 Compute:

$$\text{contrast_sensitivity} = \text{Barten_CSF_model}(u, L)$$

$$\text{modulation_threshold} = 1/\text{contrast_sensitivity}$$
 - B. Using the *LOW* image data and *DETAIL_MAGNITUDE* image data, compute the modulation of the 4K–8K luminance detail:

$$\text{Modulation of detail} = (L_{\text{max}} - L_{\text{min}})/(L_{\text{max}} + L_{\text{min}}).$$
 Note that we do not have L_{max} or L_{min} only

$$L_{\text{average}} = \text{LOW}(x, y) \text{ and } L_{\text{magnitude}} = \text{DETAIL_MAGNITUDE}(x, y).$$
 Now, substitute

$$L_{\text{max}} = L_{\text{average}} + L_{\text{magnitude}}$$

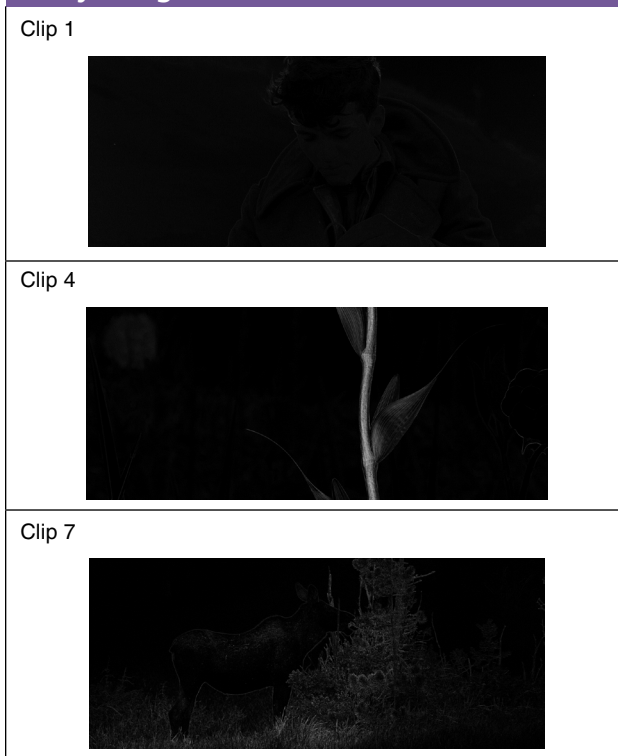
$$L_{\text{min}} = L_{\text{average}} - L_{\text{magnitude}}$$
 Into the equation for modulation of detail = $(L_{\text{max}} - L_{\text{min}})/(L_{\text{max}} + L_{\text{min}})$

$$= L_{\text{magnitude}}/L_{\text{average}}$$

$$= \text{DETAIL_MAGNITUDE}(x, y)/\text{LOW}(x, y)$$
 - C. Compute the number of JNDs due to 4K-to-8K high-frequency detail for this pixel as the ratio between the modulation of detail and the modulation threshold:

$$\text{JNDs}(x, y) = \text{modulation of detail}/\text{modulation threshold}$$
5. Compute the percentile of the JND image data.

TABLE 6. JND images output from high frequency detail visibility content analysis algorithm.



Characteristics of Best Performing Content

Tying the high frequency detail visibility content analysis to the score performance, it appears that when the viewers had excellent “20/10 Vision” and the clips had a significant number of pixels with strong enough high frequency detail to be visible according to the Barten Contrast Sensitivity function, the viewers did indeed score those clips higher when they were shown with 8K resolution instead of 4K resolution.

Conclusion

On the basis of the perceptual analysis discussed in this paper, we can draw several conclusions. The test results show that increasing resolution from 4K to 8K under typical viewing conditions did not result in a significantly improved visual experience. Additionally, the testing showed that the perceptual difference seems to be highly content dependent, and after performing a frequency and visibility analysis of the content, we could validate that content with a strong enough high frequency detail was indeed more perceptible for the participants in the study.

Similarly, we could confirm that the perceptual difference is closely tied to the vision science aspects. Viewers with 20/20 or better vision in general performed better than viewers with worse than “20/20 Vision,” and participants with “20/10 Vision” in the front row confidently rated two of the 8K clips as “Slightly Better.”

Furthermore, 27% of participants had better than “20/20 Vision.” Since the current ITU-R for viewing distances is based on viewers having “20/20 Vision,” perhaps these industry guidelines and recommendations could be re-evaluated. Considering the significant number of

The percentile of JND plots shown in **Fig. 10** quantifies the percentage of pixels that exhibit strong visibility of 4K–8K detail among the different clips.

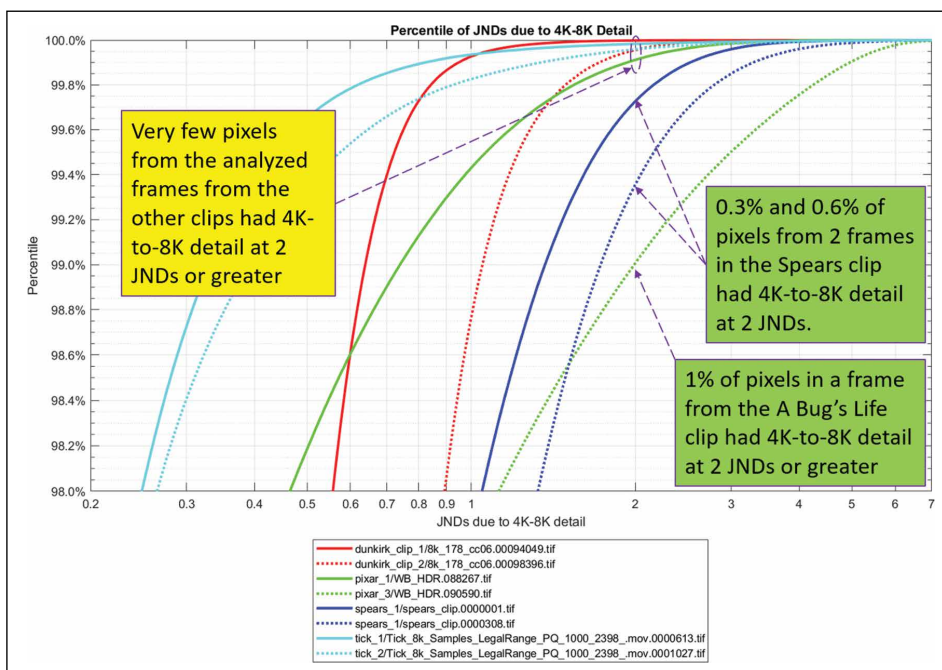


FIGURE 10. Percentile of JNDs due to 4K to 8K detail.

viewers with better vision, the recommendations could be updated to also include guidelines for viewers with 20/10 and 20/15 vision.

Acknowledgments

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About the Authors



Michael D. Smith has been a digital imaging and intellectual property consultant since 2003. He is currently the co-editor of the Joint Photographic Experts Group (JPEG) 2000 high-throughput image compression standard. In 2018, he received a screen credit for his work on

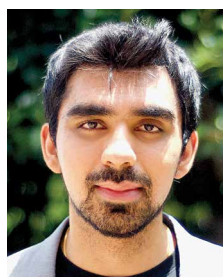
Mary Poppins Returns which was related to the color science involved in integrating a traditional 2D animation workflow with a modern ACES production pipeline. From 2013 to 2015, he was the co-chair of Blu-ray

Disc Association’s ultrahigh-definition task force (UHDTF) Video Subgroup, which defined the video-related requirements for the UHD Blu-ray disc format. His work on more than 35 intellectual property matters related to infringement and validity of patents has resulted in payments of approximately \$1.7 billion. He was the editor of the book “3D Cinema and Television Technology: The First 100 Years” published by SMPTE in 2011. He received the BS and MS degrees in electrical engineering from the University of California at Los Angeles (UCLA), Los Angeles, CA, in 2001 and 2004, respectively.



Michael Zink is the vice president of technology at Warner Bros. (WB), Burbank, CA, where he is responsible for exploring emerging technologies to enhance WB’s capabilities for production, post-production, and distribution. This includes assessing new technologies and assisting with the setup

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