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# The Impact of Adaptation Time in High Dynamic Range Luminance Transitions

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**Abstract.** *Modern production and distribution workflows have allowed for high dynamic range (HDR) imagery to become widespread. It has made a positive impact in the creative industry and improved image quality on consumer devices. Akin to the dynamics of loudness in audio, it is predicted that the increased luminance range allowed by HDR ecosystems could introduce unintended, high-magnitude changes. These luminance changes could occur at program transitions, advertisement insertions, and channel change operations. In this article, we present findings from a psychophysical experiment conducted to evaluate three components of HDR luminance changes: the magnitude of the change, the direction of the change (darker or brighter), and the adaptation time. Results confirm that all three components exert significant influence. We find that increasing either the magnitude of the luminance or the adaptation time results in more discomfort at the unintended transition. We find that transitioning from brighter to darker stimuli has a non-linear relationship with adaptation time, falling off steeply with very short durations.*

***Keywords:*** *high dynamic range imaging, psychophysics*

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## 1. INTRODUCTION

Since the ratification of ITU-R Recommendation BT.2100 in 2017 [10], the production and distribution of high dynamic range (HDR) content has increased exponentially. Industry creatives have leveraged a new set of tools that expose audiences to increased detail in both deeply dark and expansively bright imagery. Creatives may want to intentionally exploit the extended luminance range and introduce high-magnitude changes within their content. While this represents a positive advancement for artistic expression, it also increases the potential for sudden, unintended luminance jumps when programs are edited together. There are several cases in which abrupt, large changes in luminance are neither authored by creatives nor preferred by audiences. Examples include changes that occur at program transitions, advertisement insertions, social media mixed feeds, and channel changes. These unintended changes in luminance both disrupt the creative intent of the original content and provide the audience with an unsatisfactory experience. It is of interest to understand the underlying phenomena driving the audience's reaction in these scenarios.

Quantifying the magnitude of the luminance jump provides the first indication of how impactful the transition is going to be. However, simply recognizing the differences in luminance level at either end of the transition cannot, alone, characterize the visual experience. The direction of the change will also impact the nature of the reaction. A transition that increases in luminance will provide a different experience than one that decreases in it. This article highlights the adaptation time in which the audience was subjected to one luminance level before switching to another. Adaptation time is defined as a third, major contributing factor to the audience's response. New subjective testing is described to evaluate the effects of increasing and decreasing adaptation time on the comfort level experienced during HDR luminance transitions.

## 2. BACKGROUND

There is an abundance of research describing luminance perception and adaptation. Of particular interest to this study is the human visual system's reaction to the sequential presentation of various images with distinguishably different luminance levels. This phenomenon involves understanding the interpretation of mean display luminance levels and exploring the influence of adaptation.

### 2.1 *Luminance Perception Terminology*

The appearance of projected images is inherently tied to the human visual system's perception of light. This phenomenon is elucidated by the Commission Internationale de L'Eclairage (CIE) through the field of physical photometry. The visual response to light levels will vary from person-to-person. Because of this, a series of efficiency functions were defined to represent responses for a standard observer. These functions are used alongside International System of Units (SI) to calculate photometric quantities of physical radiometry [6]. Of these quantities, luminous intensity (or simply, luminance) is the photometrically-scaled measurement of physical intensity [7].

While luminance is the photometric term assigned to light's measurable quantity, the CIE defined additional terms to describe its perception. "Brightness" is the attribute of a physical sensation according to which a given visual stimulus

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appears to be more or less intense [7]. “Lightness,” by contrast, describes perceived intensity relative to a similarly illuminated stimulus that appears to be white [7]. These distinctions between the two perceptual phenomena remain relevant in modern research.

Wyszecki expanded on the CIE’s definition of brightness to include cases in which areas occupied by a visible stimulus appear to emit more or less light [25]. Arend, however, offered a streamlined interpretation by suggesting that brightness is “apparent luminance” [1]. This definition has become more common in psychophysics due to it being a reactionary term affiliated with early processing in the visual system. Regarding brightness this way defines it as an appearance-based percept that can help interpret the underlying neural processes behind judgements of luminance [4]. These neural mechanisms are commonly explored through human reactions to visual illusions [5]. However, this interpretation of brightness can shine light on neural processing mechanisms such as photoreceptor light adaptation.

### 2.2 *Perceivable Luminance Differences*

The visual system’s sensation of luminous intensity has a non-linear relationship with the intensity’s magnitude. With that said, it is possible for a stimulus to change in luminance without subjects perceiving a difference. For more than one hundred fifty years, experiments and publications have come forward to suggest a trend that describes luminance difference detection across various intensity values. The human visual system’s ability to distinguish two luminance levels as distinct from one another is measured in units of just noticeable difference (JND) values; first coined by Weber. In the same publication, Fechner introduced a logarithmic relationship to describe the relationship between luminance sensation and magnitude [8]. The trend illustrated how geometric (or multiplication-based) progressions in stimulus magnitude would correspond to arithmetic (or addition-based) progressions in stimulus sensation. Stevens, on the other hand, proposed the relationship should take the form of a power function and widen the range of magnitude-sensation comparisons [23].

Bartleson and Breneman conducted a series of experiments that found an exponential-decay-type trend forms following a simple power relationship [3]. Both screen luminance and surround luminance were incorporated into the design of this relationship. In recent years, the perceptual quantizer (PQ) aimed to characterize JNDs from the inverse of the Barten contrast sensitivity function [13]. It is worthwhile to note that the attempted perceptual scaling of luminance does not correlate directly with the scaling of luminance differences between stimuli. Regardless of their form, JND models aim to compare luminance levels on the basis of how differently they appear from one another.

While perceptual models are based on controlled stimuli of uniform luminance values, digital complex imagery contains a wide spectrum of pixels that depict differing luminance levels. It is believed that observers viewing the image visually interpolate the presented luminance information and adapt to a mean display level. Noland et al. devised a user study evaluating ten objective metrics that estimate the mean perceived image luminance level [15]. From this study, it was determined that simply finding the image’s mean display luminance provided a good estimate of its overall perceived level. This methodology was utilized to estimate the mean display luminance of the images shown in the presented study.

HDR images, by their very nature offer a wide array of luminance ranges in a single frame. With that said, there is ample opportunity for observers to adapt to local regions of differing luminance within a single image. While local adaptation is an important consideration for viewing HDR imagery, this research is specifically focused on cases where HDR images appear “flatter” and exhibit uniformly distributed luminance values.

### 2.3 *Adaptation Time Course*

The mechanics of visual adaptation take influence from the two classes of photoreceptors in the human eye. By nature of their physiology, rods and cones behave differently when the visual system is subjected to various lighting environments. Cones drive the response to photopic vision situations (luminance levels above 0.03 cd/m$^2$). In these instances, the rod photopigment (rhodopsin) is bleached and does not contribute to perception. By contrast, scotopic (dark) vision is driven by the mechanics of the rods with little influence from the cones. Both rods and cones work in tandem in mesopic vision scenarios, which act as a transitionary stage between the photopic and scotopic regions [12].

When the visual system is transitioning to darker luminance levels from brighter ones, the rod sensitivity steadily improves as the cone sensitivity decreases. The time course of rhodopsin regeneration is very slow but it’s also dependent on the pre-adaptation luminance level. Preexposure to luminance levels of a greater or lesser magnitude to the target, dark adaptation level will affect the time required to reach the steady-state level. Generally speaking, the rod sensitivity tends to reach the scotopic threshold following more than five minutes of adaptation [12]. Light adaptation is a much quicker process, where the eye adjusts its pupil diameter to avoid over-saturating its cone response. Photopic adaptation states also take influence from other environmental and physiological factors such as the size of the adapting field, age of the subject, and number of eyes viewing the scene [24].

As discussed, the human visual system shifts its adaptation state over time as a means of acclimating to illumination changes in its environment. This phenomenon holds true when displaying HDR imagery in a controlled setting. A continuous presentation of images depicting a constant mean luminance level will allow for the visual system’s adaptation to reach a steady state position. Transitions to images reflecting significant deviations above or below this steady-state level will induce a reaction in the visual system. Based on the magnitude of the difference between the steady-state and newly introduced luminance level, the time required for complete adaptation changes. Smaller differences in luminance will require shorter adaptation times and sometimes occur without the subject recognizing the change. As one might expect, larger differences will evoke a longer adjustment period for the subject's visual system following initial exposure [2].

### 2.4 *Related Research*

Quantifying subject reactions to screen luminance changes is commonplace. Part of this study is done to measure subjective preferences for luminance levels. For instance, Guterman et al. conducted an experiment where subjects rated their preferences for average luminance level of natural images [9]. The test was run using a projector set-up and produced results indicating that observer preferences began to plateau after 130 cd/m$^2$. Ths study did not consider how industry professionals use extended luminance ranges for creative effect.

With respect to viewing comfort, work has been done to assess thresholds where luminance levels induce physical reactions from the human eye. Shi et al. performed a study that involved tracking of subjects' eye movements as they were subjected to video sequences of differing mean display luminance levels [19]. The study was performed on an HDR display in a dim surround environment. Recorded results of the participants' eye movements indicated the presence of visual fatigue during sequences of higher mean display luminance levels.

The concept of switching between HDR imagery of various luminance differences was previously tackled by Noland and Pindoria [16]. Their study aimed to evaluate observer response to HDR luminance changes of varying magnitude. The motivation behind their work was to gauge the impact of HDR transitions that were not authored for creative effect but, instead, occurred unintentionally. Subjects were first presented with an HDR image for ten seconds before it switched to another HDR image of differing mean display luminance. Following the change, the subjects rated their experience with the luminance transition via an impairment scale. The results offered potential tolerance levels for unexpected and unintended luminance changes.

A similar experiment was conducted by Ploumis et al. to assess subjective reactions to unexpected luminance changes in a cinema environment [17]. Their study had participants adapt to a reference luminance level before proceeding with the transition. To determine the influence of color on observer responses, luminance transitions between red, green, blue, and white color frames were evaluated. Results from the study indicated that single-channel (one color) luminance transitions will evoke a comparable response to white luminance transitions at the same luminance level.

While Ploumis et al. and Noland/Pindoria highlighted the important role played by the luminance changes' magnitude, it is of interest to explore the impact of adaptation time. As discussed, the duration of preexposure plays a role in the time required to reach steady-state adaptation. The longer that the visual system is exposed to the previous stimulus, the more time will be required for a new adaptation state to be reached [14]. On top of this, it is expected for the changes in preexposure duration to also affect observer reactions to the initial change between HDR luminance levels.

### 2.5 *Subjective Testing*

A new set of subjective experiments was devised to evaluate the impact adaptation time has on visual comfort at unexpected HDR luminance transitions. Similar to previous subjective studies, this research aims to measure the degree of discomfort and/or annoyance observers feel at transitions of varying magnitude. It was hypothesized that the results are comparable to those published by Noland and Pindoria.

While the Noland/Pindoria publication helps form expectations as to how magnitude will play a role in the luminance-change test, it doesn't offer a suggestion for how adaptation time will impact the results. Although the observer responses were predicted to differ depending on luminance-change magnitude, it was expected that all three of them will follow a similar trend.

## 3. METHODOLOGY

As discussed, the subjective experiments were designed to evaluate the effects of the luminance-change magnitude as well as the adaptation time. Also considered was the direction of the change (darker or brighter). Understanding that dark adaptation is slower than light adaptation, there is an expectation for transitions reflecting a dark-to-bright change to result in a different observer response than those reflecting a bright-to-dark one. Because of the impact the direction of the luminance change has on the subject's adaptation, the experiment was split into two parts. The first part tested the dark-to-bright scenario, while the second part tested the bright-to-dark one. Splitting the experiment into two parts both ensured a consistent adaptation procedure and prevented observer fatigue. It is highly possible that the results would have skewed, had the observers been asked to rapidly switch between a predominantly dark adaptation state and a predominantly bright one between trials.

When designing the workflow, it was desired to keep the adaptation procedure consistent, trial to trial. Instead of presenting two images (one to adapt to and one to change to) per trial, we presented three images. The first and third images were the same. By having the primary adaptation happen on the second of the three images, this workflow prevented the adaptation state of the subjects from varying. This design also allowed for the experiment to closely mimic a channel change operation. The luminance transitions simulated a situation where an observer starts on one channel, switches to another one, and finally changes back to the starting one.

Figure 1 illustrates the experimental procedure that was followed for the bright-to-dark-to-bright adaptation version of the experiment. After providing demographic information and issuing consent to participate in the test, each subject

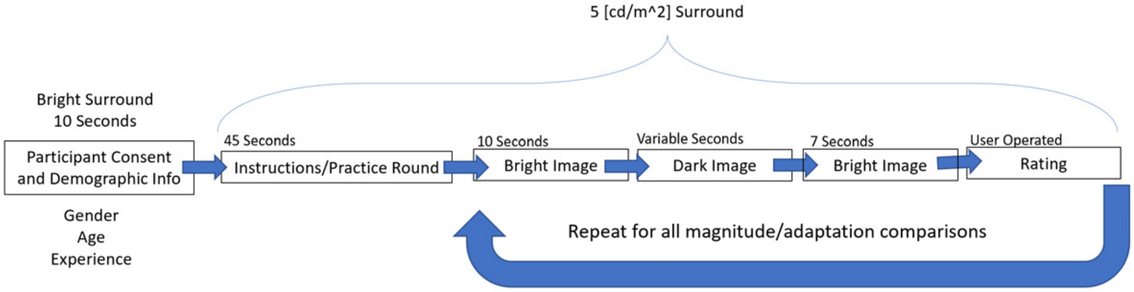

Figure 1. Procedure for the bright-to-dark-to-bright version of the experiment.

**Table I.** Variable durations of adaptation time.

| Experiment | Duration (seconds) |
|---|---|
| Bright-to-Dark-to-Bright | 0.5, 5, 10, 25, 40, 60, 90, 120, 150 |
| Dark-to-Bright-to-Dark | 0.5, 2, 5, 10, 15, 20, 30, 60 |

was brought into a 5 cd/m$^2$ surround environment. Before the main experiment, the subjects were given instructions and participated in a short practice round. Each trial started by showing a bright image for ten seconds. Following this, a dark image was presented for a variable amount of time. Finally, the bright image was shown again for seven seconds, and the observer was asked to rate the visual experience. The ratings were based off the observers' immediate sensation when the dark image switched back to the bright one. The dark-to-bright-to-dark adaptation version of the experiment followed a similar procedure. First, a dark image was presented for ten seconds, followed by a bright image for a variable amount of time, before the dark image returned to the screen for seven seconds. The observers, once again, rated the sensation immediately following the switch from the bright image back to the dark one.

To test the influence of adaptation time, the duration in which the observer is subjected to the second channel varied between trials. As discussed, dark and light adaptation are processed at different speeds. For this reason, it was deemed necessary for the two versions of the experiment to test different adaptation durations. A series of beta studies determined the optimal durations for each version; shown in Table I.

As previously mentioned, subjects were asked to rate their experience following the second transition. To gauge the impact of the transition, observers were asked to make their selections based on their immediate reaction to the transition. Originally, the five-grade impairment scale described in ITU-R BT.500 [11] was used. During the beta testing period, however, observers struggled to apply this rating scale to the experimental task.

Because all images exhibited notably different mean display luminance values, observers were confused with the score of "5," which denotes "imperceptible difference." The observers also felt limited in their responses for the ratings that indicate an "annoying" experience. Many of our subjects asked to have more gradation in those choices. In addition to feedback about the mechanics of the impairment scale, observers felt the term "annoying" did not apply to the bright-to-dark-to-bright transitions. It was better understood when the experience was described as "painful," to match the physical sensation in their eyes. However, the observers accepted the term "annoying" for the dark-to-bright-to-dark transitions. The observers felt it appropriately described the inability to discern dark detail following bright adaptation.

**Table II.** Impairment scale used to rank the transition for both versions of the experiment.

| Rating | Terminology [Dark-to-Bright/Bright-to-Dark] |
|---|---|
| 4 | Not painful/annoying |
| 3.5, 3 | Slightly painful/annoying |
| 2.5, 2 | Notably painful/annoying |
| 1.5, 1 | Painful/Annoying |

Using a combination of the feedback from beta observers and influence from the eleven-grade numerical scale specified in ITU-R BT.500, a new seven-grade impairment scale was implemented. The scores and terminology affiliated with the new impairment scale are shown in Table II. There are two values given to terms that indicate a degree of pain or annoyance to add gradation in the responses. As mentioned, the two versions of the test use different language to reflect the observer feelings following the luminance transition.

A total of seventeen participants completed the experiment. Ten of the participants were female, while the other seven were male. Fifteen of the participants were in either their twenties or thirties, while the other two were in their fifties. Ten of the participants were familiar with either color science or image evaluation. Seven observers had not previously participated in a subjective test. All seventeen of the participants were informed of the experiment's procedure before both versions and agreed to take part in it twice.

### 3.1 *Stimuli and Procedure*

The viewing conditions of the experiment matched those presented within ITU-R BT.2100. A 5 cd/m$^2$ luminance

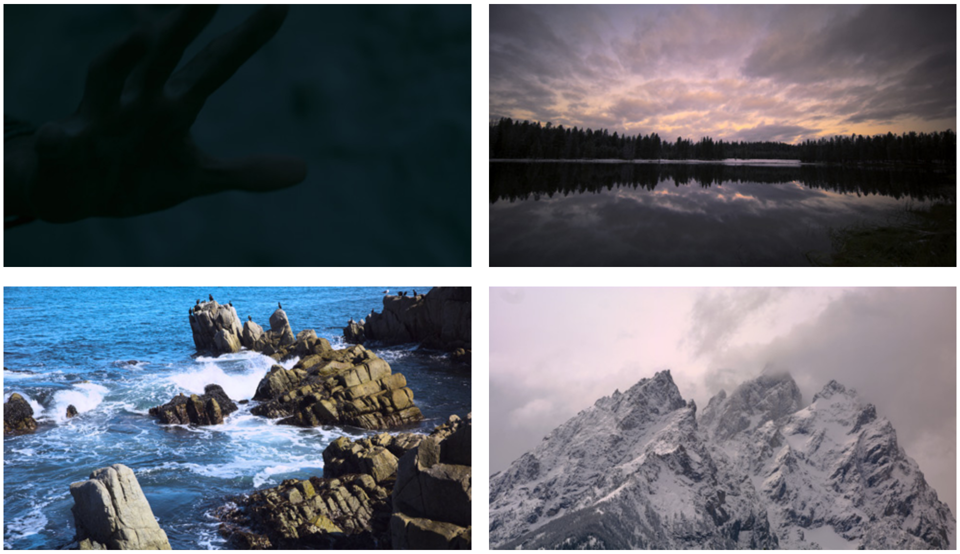

Figure 2. Test images.

surround was implemented with a Christie 4K 6P laser projector system. The laser projector was calibrated to a peak luminance of 1000 cd/m$^2$ and had a measured black level of 0.0004 cd/m$^2$. A total of four images were used in this study (shown in Figure 2). The top image served as the "dark" image, while the other three each served as different levels of the "bright" image. The dark image was created by Dolby Laboratories, Inc. (Dolby) and the three bright images were licensed to Dolby by Spears & Munsil [22]. The dark image reflected a mean display luminance value of 0.1 cd/m$^2$, while the three bright images reflected mean display luminance values of 20 cd/m$^2$, 100 cd/m$^2$, and 338 cd/m$^2$.

It is important to note that the images in this study represent unusual cases of HDR content, where the luminance distribution is fairly flat. Typical HDR imagery utilizes the high peak luminance more dynamically and, usually, depicts lower mean values. The selection of these images was intentional so that observers would have a consistent viewing experience regardless of what region of the image their gaze attended to. Had the images been dynamic and displayed a range of luminance detail, the observers would have had the opportunity to view various regions with differing luminance. That, in turn, would have influenced their response and added noise to the experimental results. The three bright images, however, exhibited different color palettes from one another. This may have influenced observer sensations and should be controlled better in future experiments. To mathematically visualize the spatial differences between the three bright images and the dark image, Table III logs the root-mean-squared (RMS) contrast between the three bright images and the dark image.

$$\text{RMS Contrast} = \sqrt{\text{mean}((\text{bright image} - \text{dark image})^2)}.$$

All images were within the luminance range of the projector. The images were situated such that they subtended a horizontal angle of 33° from the observer's viewing position. This corresponds to three picture heights. A black border was added to the image to simulate the appearance of a television, while the remainder of the screen showcased a 5 cd/m$^2$ luminance surround. The image signal was encoded with the SMPTE ST 2084 electro optic transfer function (PQ) [21] before being transferred to the projector over standard digital interface (SDI). Figure 3 depicts the experimental setup.

**Table III.** RMS contrast calculated between the three bright images and the dark image.

| Mean Display Luminance (cd/m$^2$) | RMS Contrast with "Dark" |
|---|---|
| 20 | 36 |
| 100 | 192 |
| 338 | 409 |

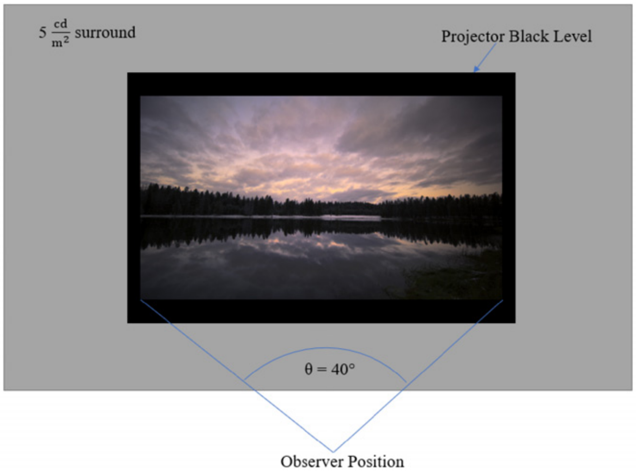

Figure 3. Experimental setup and environment.

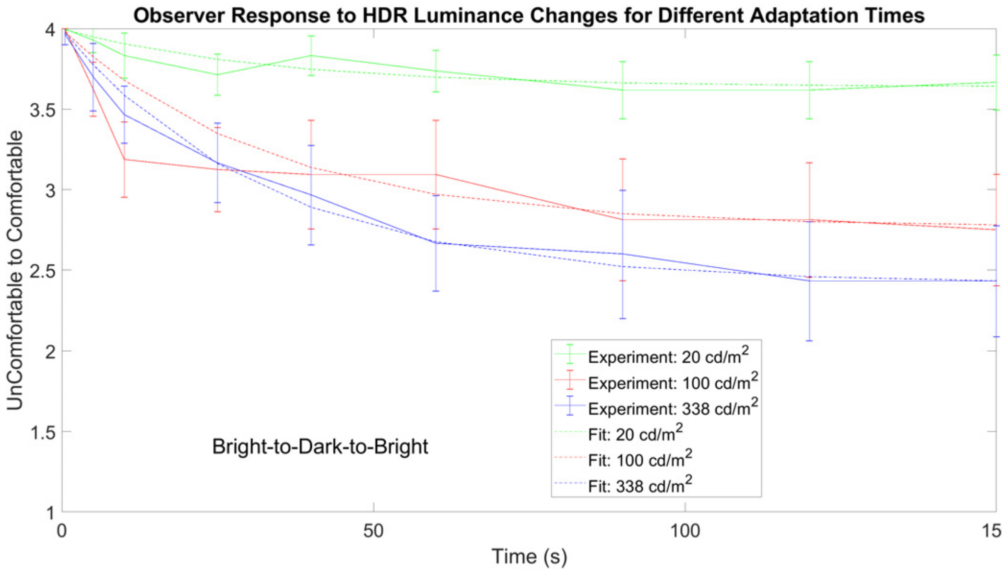

Figure 4. MSS for three luminance transitions across differing adaptation times in the bright-to-dark-to-bright experiment.

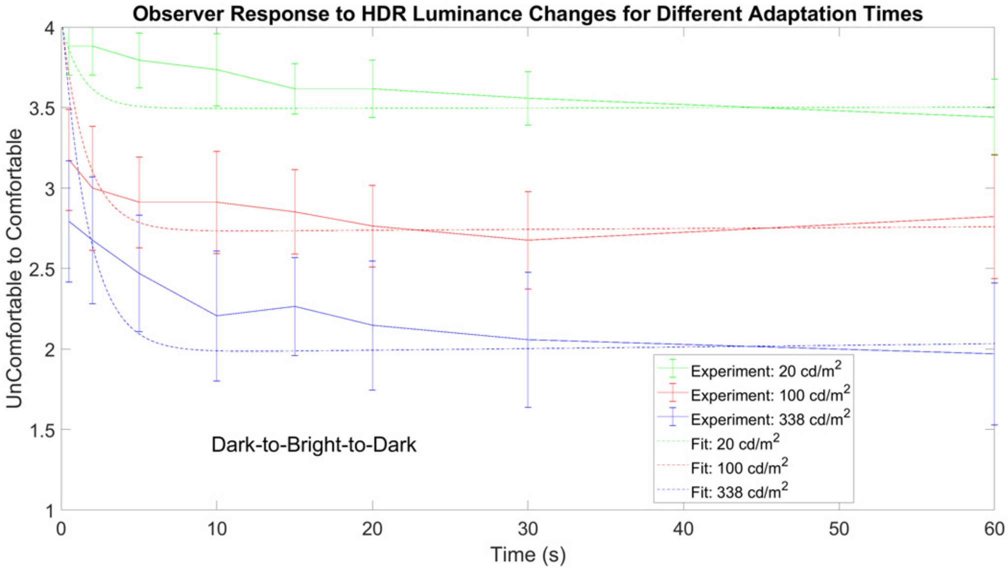

Figure 5. MSS for three luminance transitions across differing adaptation times in the dark-to-bright-to-dark experiment.

## 4. RESULTS

Within the two versions of the experiment, three different transitions were evaluated between bright and dark images across different adaptation time periods. By modelling the results, we explore the influence adaptation time brings to the mean subjective score (MSS) for the two experiment conditions. The fitted trends were approximated by implementing a model derived by Smirnakos et al. [20]. The linear luminance values were scaled to PQ and time was sampled based on image frames. The time constants were calculated based on a frame rate of 24 fps.

$$\mathrm{Fit}(t) = \begin{cases} \mathrm{Luminance}(t) & \text{if } t = 0 \\ \frac{\tau}{\tau+1}\left(\mathrm{Fit}(t-1) + \frac{\mathrm{Luminance}(t)}{\tau}\right) & \text{if } t > 0, \end{cases}$$

where $t$ is the frame number and $\tau$ is the characteristic time of decay; a constant which is determined from:

$$p(t) = \begin{cases} 1 & \text{if } t = 0 \\ \mathrm{Luminance}(t) - \mathrm{Fit}(t-1) & \text{if } t > 0 \end{cases}$$

$$\tau = \begin{cases} 25 & \text{if } p(t) \geq 0 \\ 850 & \text{if } p(t) < 0, \end{cases}$$

Figures 4 and 5 show the MSS values and 95% confidence intervals for the three images across the nine adaptation time trials. Fig. 4 corresponds to the bright-to-dark-to-bright experiment, while Fig. 5 reflects the dark-to-bright-to-dark one. As mentioned previously, the ratings scale was created based on impairment scales presented in ITU-R BT.500. An

MSS of 4 represents a transition which does not introduce any disruption in observer comfort, while scores at or below 2 suggest a noteworthy change in experience.

A repeated-measures analysis of variance (ANOVA) test was run to compare the mean selections for the three luminance-change cases in each of the two experiments. Statistical significance was confirmed in the results of all three luminance levels within a 95% confidence interval [18] across two degrees of freedom for both experiments. The results of the bright-to-dark-to-bright experiment exhibited an F-statistic of 8.1 and a p-value of 0.002, while those of the dark-to-bright-to-dark experiment exhibited an F-statistic of 83.6 and a p-value of $1.004 \times 10^{-10}$.

The results of the bright-to-dark-to-bright experiment confirm that the MSS values are influenced by the magnitude of the luminance change and the adaptation time. The data suggests that observers will find the experience more comfortable when the magnitude of the difference is lowered and/or the adaptation time is shortened. The MSS values begin to reach a plateau for all three cases at the largest adaptation time values. As mentioned previously, this was expected based on the initial testing done to select the adaptation time durations and prior modelling of this phenomenon.

The results of the dark-to-bright-to-dark experiment similarly confirm that the MSS values take influence from the luminance change magnitude and the adaptation time. All three cases in this experiment, however, exhibit some level of annoyance at the one-half second duration. Even at this short duration, the observers experienced perceptual afterimage artifacts caused by the bright image. At this one-half second trial, the annoyance level was seen to be higher for each of the three cases. This confirms the influence of luminance-change magnitude on observer responses and suggests a non-linear relationship. Despite the different starting points, the results of all three cases ease into a plateau at the higher time course values.

Looking, first, at the case where the observers switch from the 20 cd/m$^2$ image to the dark image in Fig. 5, the results convey a comfortable experience for all trials. Only in the last trial, which subjected observers to a one-minute adaptation time course, there was an indication of slight annoyance by the MSS values. Where the observers adapt to the 100 cd/m$^2$ image and the 338 cd/m$^2$ image, a decrease in the comfort level was immediately seen. This trend of increasing the luminance-change magnitude was expected. Being adapted to a brighter luminance level will increase the time necessary to shift viewer adaptation down to a darker one. Following the decrease in luminance, the observers found the experience of waiting to see the details in the dark image unfavorable. The larger the magnitude of the luminance change, the more annoying the experience. Adapting to the 100 cd/m$^2$ image saw slight annoyance in the MSS values, while adapting to the 338 cd/m$^2$ image saw MSS values indicating notable annoyance. Despite following a non-linear trend, the observer results align with the findings of Noland and Pindoria at the 10 second mark (matching their experiment design).

## 5. DISCUSSION

While this experiment shined light on how observers respond to sudden luminance changes, it does not cover the problem in full. As discussed, the observer response to luminance changes was evaluated along the lines of the changes' magnitude, direction, and adaptation time. Aligning these components with one another in different respects allowed for their individual influences to take impact on comfort level. One major difference between the two versions of the experiment was the descriptive language of the MSS choices. While swapping out "annoyance" with "pain" helped observers distinguish the difference between the cases, it may have made the results between the two versions disproportionate. It's entirely possible that an observer didn't experience any eye pain during a bright-to-dark-to-bright trial but was somewhat annoyed by the change. This level of scrutiny does not exist in the presented data. It would be helpful to ensure that the responses between the two versions are distributed evenly.

In the context of this study, participants were instructed to respond to the immediate change in luminance. While this provides insight into the reaction following the transition, it does not cover the duration of the initial response or how it changes over time. It is likely that the level of discomfort becomes lower very quickly after the bright-to-dark-to-bright transition. Similarly, few observers might not mind the dark-to-bright-to-dark transition, if the details in the dark image become visible shortly after the change. This phenomenon, in a sense, represents a secondary adaptation parameter that exists following the luminance change. Further investigation into the longevity of the initial response can help complete the visual model.

As stated previously, the study was designed to mimic a channel change operation. While the emphasis was on the second transition that brought the observer back to the previous "channel," no consideration was given to either the first transition or how the two transitions operated together. Considering the experience collectively could cater the response to an evaluation of why the second channel "interrupts" the first one. For example, if bright content interrupted dark content for a very short duration, it would likely be viewed as more visually annoying than if it lasted a long duration. It's also possible that the opposite results would occur in the reverse situation of dark content unexpectedly interrupting bright content. Expanding the problem's scope from one transition in luminance to a more-complete scenario can provide insight into additional components of the visual experience.

## 6. CONCLUSION

This research explored three luminance-transition components that influence observer responses: the magnitude of the of change, the direction of the change (darker or brighter), and the adaptation time before the change. The presented results confirm that all three components provide significant influence. Increasing or decreasing the magnitude of the luminance change will impact the comfort level of the observer in a similar way to increasing or decreasing the adaptation time. In television and social media, there are often program transitions, advertisement insertions, and channel change operations. We have shown that these unexpected transitions have the potential to cause visual discomfort or annoyance. A surprising result was the non-linear subjective responses with the dark-to-bright-to-dark transition, which fell sharply with little adaptation time. Further study is needed to verify what caused this. Additional opportunities for further study include investigating the longevity of the response after the luminance change and extending the problem to include multiple luminance transitions that occur sequentially. Furthermore, the influences of color palette and local adaptation are yet to be explored. Regardless, this research provided insight into how human subjects respond to unintended luminance changes across varying periods of adaptation.

## REFERENCES

[1] L. E. Arend, "Mesopic lightness, brightness, and brightness contrast," Percept. Psychophys. **54**, 469–476 (1993) (PubMed: 8255709).

[2] H. B. Barlow, *Dark and Light Adaptation: Psychophysics* (Springer, Berlin, Heidelberg, 1972), pp. 1–28.

[3] C. J. Bartleson and E. J. Breneman, "Brightness perception in complex fields," J. Opt. Soc. Am. **57**, 953–957 (1967).

[4] B. Blakeslee and M. E. McCourt, "A common theoretical framework for brightness and lightness perception," Perception **44**, 359–362 (2015).

[5] B. Blakeslee and M. E. McCourt, "What visual illusions tell us about underlying neural mechanisms and observer strategies for tackling the inverse problem of achromatic perception," Front. Hum. Neurosci. **9**, 205 (2015).

[6] Commission Internationale de l'Eclairage 23539:2023, "Photometry--The CIE System of Physical Photometry".

[7] CIE. International Lighting Vocabulary. 3rd. Bureau Central de la CIE; Paris: 1970. Publ. No. 17, (E1.1).

[8] G. T. Fechner, *Elemente der Psychophysik* (Leipzig, Breitkopf und Härtel, 1860), p. 136.

[9] P. S. Guterman, L. M. Wilcox, R. S. Allison, and K. Fukuda, "75.3: Is brighter always better? the effects of display and ambient luminance on preferences for digital signage," *SID Symposium Digest of Technical Papers* (Wiley, Hoboken, NJ, 2010), Vol. 41, p. 1116.

[10] International Telecommunication Union – Radiocommunication (ITU-R), Recommendation BT. 2100, "Image Parameter Values for High Dynamic Range Television for Use in Production and International Programme Exchange," (2017).

[11] International Telecommunication Union–Radiocommunication (ITU-R), Recommendation BT. 500-15, "Methodologies for the Subjective Assessment of the Quality of Television Images," (2023).

[12] M. Kalloniatis and C. Luu, "Light and dark adaptation (2005, Updated 2007)," *Webvision: The Organization of the Retina and Visual System [Internet]* (University of Utah Health Sciences Center, Salt Lake City, UT, 1995), Available from https://www.ncbi.nlm.nih.gov/books/NBK11525/.

[13] S. Miller, M. Nezamabadi, and S. Daly, "Perceptual signal coding for more efficient usage of bit codes," SMPTE Motion Imaging J. **122**, 52–59 (2013).

[14] F. A. Mote and A. J. Riopelle, "The effect of varying the intensity and the duration of preexposure upon foveal dark adaptation in the human eye," J. Gen. Physiol. **34**, 657–674 (1951).

[15] K. C. Noland, M. Pindoria, and A. Cotton, "Modeling brightness perception for high dynamic range television," *Presented at the Ninth Int'l. Conf. Quality of Multimedia Experience* (IEEE, Piscataway, NJ, 2017).

[16] K. C. Noland and M. Pindoria, "A brightness measure for high dynamic range television," SMPTE Motion Imaging J. **127**, 55–61 (2018).

[17] S. Ploumis, R. Boitard, G. Damberg, A. Ballestad, and P. Nasiopoulos, "Brightness in Cinema: When is it too bright?," *SMPTE 2019* (IEEE, Piscataway, NJ, 2019), pp. 1–17.

[18] A. Ross and V. L. Willson, "One-way Anova," *Basic and Advanced Statistical Tests* (Sense Publishers, Rotterdam, 2017), pp. 21–22.

[19] Y. Shi, Y. Tu, L. Wang, and X. Gao, "P-33: Effects of luminance, contrast and saturation of HDR QLED display on visual system based on eye movement," *SID Symposium Digest of Technical Papers* (Wiley, Hoboken, NJ, 2019), Vol. 50, pp. 1358–1361.

[20] S. M. Smirnakos, M. J. Berry, D. K. Warland, W. Bialek, and M. Meister, "Adaptation of retinal processing to image contrast and spatial scale," Nature **386**, 69–73 (1997) PMID: 9052781.

[21] Society of Motion Picture and Television Engineers (SMPTE), ST 2084:2014, "High dynamic range electro-optical transfer function of mastering reference displays".

[22] Spears & Munsil Ultra HD Benchmark (2023). Available: https://www.biaslighting.com/products/spears-munsil-ultra-hd-benchmark-2023.

[23] S. S. Stevens, "On the psychophysical law," Psychol. Rev. **64**, 153–181 (1957).

[24] A. B. Watson and J. I. Yellott, "A unified formula for light-adapted pupil size," J. Vis. **12** (2012).

[25] G. Wyszecki, "Color appearance," *Handbook of Perception and Human Performance*, Sensory Processes and Perception (John Wiley and Sons, New York, NY, 1986), Vol. 1.