https://doi.org/10.2352/CIC.2022.30.1.38

Suprathreshold contrast matching between different luminance levels

***Maliha Ashraf*[1]*, Rafał K. Mantiuk*[2]*, Jasna Martinovic*[3]*, Sophie Wuerger*[1]**
[1] ***Department of Psychology, University of Liverpool, United Kingdom***
[2] ***Department of Computer Science and Technology, University of Cambridge, United Kingdom***
[3] ***School of Philosophy, Psychology and Language Sciences, University of Edinburgh, United Kingdom***

Abstract

We investigated how perceived achromatic and chromatic contrast changes with luminance. The experiment consisted of test and reference displays viewed haploscopically, where each eye sees one of the displays. Test stimuli presented on the test display on a background of varying luminance levels (0.02, 2,20,200,2000 cd/m^2) were matched in perceived contrast to reference stimuli presented on a background at a fixed 200 cd/m^2 luminance level. We found that approximate contrast constancy holds at photopic luminance levels (20 cd/m^2 and above), that is, test stimuli presented at these luminance backgrounds matched when their physical contrasts were the same magnitude as the reference stimulus for most conditions. For lower background luminances, covering an extensive range of 5 log units, much higher physical contrast was required to achieve a match with the reference. This deviation from constancy was larger for lower spatial frequencies and lower pedestal suprathreshold contrasts. Our data provides the basis for new contrast retargeting models for matching appearances across luminance levels.

Introduction

Contrast vision, the ability to discern brightness or chromatic differences between areas in the visual field, is one the basic building blocks of human visual perception. It can be characterised by measuring the lowest visible contrast (threshold contrast) to different stimuli. The inverse of these measured threshold contrasts across fixed parameters (such as spatial frequency) are known as contrast sensitivity functions. These contrast sensitivity functions (CSFs) provide valuable information about the limits of human visual system. There have been a number of studies reporting contrast sensitivity functions across a range of parameters including spatial frequency [1, 2, 3], chromatic directions [4, 5], luminance [6, 7, 8], eccentricity [9, 10], temporal frequency [1, 3], stimulus size [11], age [12, 13], etc.

Human vision at higher contrast levels (also known as suprathreshold contrast vision), however, cannot be explained by contrast sensitivity functions. Studies have shown that when the contrast is sufficiently high, the response of the visual system becomes largely independent of threshold contrast of the respective stimulus [14]. For example, once physical contrast is sufficiently high, low and high spatial frequency patterns are perceived as having equal contrast, regardless of large differences between their respective threshold contrasts. This phenomenon is known as contrast constancy [14]. Contrast constancy across different spatial frequencies is an established phenomenon [14, 15, 16]. It shows that the limitations in pre-cortical mechanisms that affect

Figure 1. *Example of a retargeted image from high to low luminance. Top: Original high luminance image. Middle (to be viewed through a ND 2.0 filter): Image rendered to a low luminance level assuming contrast constancy. Bottom (to be viewed through a ND 2.0 filter): Desired rendition of low luminance retargeted image with contrasts preserved (digitally manipulated). The lower two images should be viewed with a ND 2.0 filter at a distance of approximately 0.5 m and the images zoomed to be about 5 inches on the screen. When compared with the top image, the luminance and chromatic contrast perception of the bottom rendition is preserved much better than the middle rendition at low luminance levels.*

contrasts at threshold might be compensated for at post-receptoral sites. Hence, the mechanisms governing contrast vision at threshold and suprathreshold contrast levels might be very different from each other.

In normal everyday conditions, the input to our visual system mostly consists of suprathreshold contrasts. It is therefore very important to characterise contrast perception at these high contrast levels to gain a better understanding of our visual system. The assumption of contrast constancy would be valid in most cases and would thus provide a convenient model for retargeting images across different conditions. But there is not enough unambiguous evidence to support this hypothesis for matching across very different luminance levels. Studies investigating contrast constancy across luminance levels report quite different results depending on the methodology and the range of luminance levels used [15, 17, 18]. In this study, we investigate the issue of contrast constancy, or the lack thereof, across a wide range of luminance levels.

A comprehensive dataset for contrast matching across luminance would be very useful for various image processing applications. One of the direct applications of this work would be in image retargeting for different luminance levels [19, 20]. Ultimately, the aim would be to develop a cross-luminance retargeting algorithm for complex images. For example, an HDR movie shot for a 1,000 cd/m^2 display when screened at a 50 cd/m^2 cinema screen would need to be retargeted accordingly. Figure 1 shows a high luminance image retargeted for a low luminance display. If contrast constancy is assumed, no change is made to the physical contrasts of the rendered low luminance image as the perceived contrast is assumed to be the same across luminances. But when viewing the image, we can see that the perceived contrast of the content is much lower (middle) than the original image (top). The bottom image shows an enhanced version of the dim image where contrast constancy is not assumed and the contrasts for the lower mean luminance image are increased much more than what a contrast constancy algorithm would forecast. With the increasing popularity of high dynamic range (HDR) content and technologies, the need for better algorithms for making the content adaptable to different viewing conditions is imperative.

Related work

Georgeson and Sullivan coined the term 'contrast constancy' in their seminal work [14]. They found that at suprathreshold levels, the contrast of the stimuli matched across different spatial frequencies, orientation, and retinal eccentricities was perceptually the same when the physical contrast (e.g., Michelson contrast) had the same value. Similar results are reported in other studies [21, 22, 15]. Kulikowski proposed a simple mathematical model and explanation for the contrast constancy phenomenon in matching across spatial frequency. Kulikowski's contrast matching model postulates that the difference in perceived contrast can be explained by the difference in contrast detection thresholds between two luminance levels. Specifically,

$$C_1 - C_1^t = C_2 - C_2^t \tag{1}$$

where, C_1 and C_2 are the suprathreshold contrasts of the two stimuli at two different luminance levels, and C_1^t and C_2^t are the contrast detection thresholds at the corresponding luminance levels. If C_1 and C_2 are sufficiently large (high suprathreshold contrasts) then the difference between their thresholds can be considered negligible and Equation 1 becomes $C_1 \approx C_2$. The model predicts the across-spatial frequency contrast matching functions quite well [15].

Kulikowski's work showed that the model represented in Equation 1 was also valid for contrast matching of a 5 cpd grating across a 2 log unit luminance range for multiple suprathreshold levels. Hess' work also showed similar results qualitatively for a smaller luminance range [17]. For low luminance backgrounds or low contrast stimuli, their lines of matching contrasts appear to deviate from the constancy line but the quantitative deviation in terms of threshold differences is not reported. Later studies by Peli et al. [18, 23] showed that the assumption of contrast constancy while matching across luminance levels was not valid for a wider luminance range under natural viewing. They attributed the deviation from constancy to differences in viewing conditions; differences between theirs and Kulikowski's results disappeared when similar methodologies (haploscopic viewing with longer adaptation times) were employed. However, the relevant data points only spanned 1 log unit range of luminances (Figure 6 in [23]). A later study by Peli [24] showed that the shape of across-luminance contrast matching lines also depended on spatial frequency. Although they used natural viewing conditions (no adaptation period and both eyes could see both stimuli simultaneously), their results implied that a more complex model of contrast matching was required, also taking the spatial configuration of stimuli into account.

All the aforementioned studies dealt with suprathreshold contrast in achromatic channels only. A study by Tiippana et

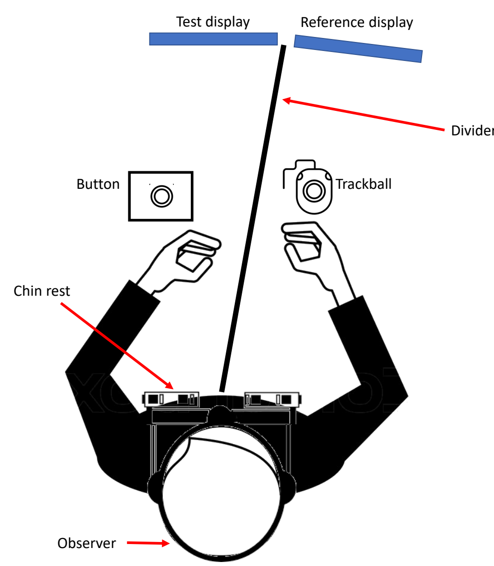

Figure 2. *Contrast matching experiment setup. The test display (HDR screen) and the reference display (SDR screen) were separated by an opaque black screen. The observers' line of sight needs to be perfectly perpendicular to the HDR display for the content to be seen correctly. The reference display has no such issue so we set it at an angle such that the viewing distances between both displays and the corresponding eyes are equal. The button and track ball are the input devices to record observers' responses.*

al. (2000) demonstrated that the principle of contrast constancy also held for chromatic contrasts when matching across spatial frequencies [25]. Delahunt et al. (2005) confirmed that contrast constancy in chromatic matches across spatial frequencies holds true for different luminance levels as well. However, their work did not investigate chromatic contrast constancy when matching across different luminance levels [26]. We found no work in the present literature which investigates contrast matching across luminance for chromatic stimuli.

Some work has been done to integrate models of contrast matching and contrast sensitivity in image retargeting algorithms. Wanat and Mantiuk [19] proposed a cross-luminance simulation framework for complex images. The model uses analytical contrast sensitivity and contrast matching functions. The contrast matching functions across luminance are adapted from Kulikowski's [15] model in a log contrast space. However, the model is not verified experimentally on a dataset. Their model takes contrast thresholds of the stimuli into account and although the threshold values are different for different spatial patterns, the same contrast matching function model is assumed regardless of spatial configuration. The model also takes only achromatic contrast mechanisms into account. Ensuing work by Rezagholizadeh et al. [20] uses Shin's [27] mesopic vision model to retarget images between different luminance levels and their framework applies to all colour channels. However, their methodology assumes no spatial dependence and only considers colour values in isolation. Therefore, our study can empirically verify the current contrast matching functions widely used in the literature and provide a dataset that can act as the basis for a more accurate data-driven model.

Apparatus and stimuli

The apparatus consisted of two screens separated by a black opaque screen as shown in Figure 2. This configuration allowed haploscopic viewing, i.e. each eye could only see one screen at the time. The left eye only saw the HDR screen, while the right eye only saw a standard dynamic range (SDR) screen with a fixed mean luminance of 200 cd/m^2. The HDR display is custom-built with 4,000 cd/m^2 peak luminance (more technical details in [8]). The SDR display is a Retina iPad screen interfaced with an Adafruit display port kit with 400 cd/m^2 peak luminance. Both the displays were luminance and colour calibrated. The stimuli were Gabor patches of spatial frequencies 0.5, 2, and 4 cycles per degree (cpd) visual angle and showed 2 cycles of a sinusoidal grating. Such fixed-cycle stimuli result in higher spatial frequency patterns being smaller in size. Three colour directions (achromatic, red-green and lime-violet) were used. Three suprathreshold contrasts were tested, that we refer to as *high, medium*, and *low* contrast conditions. 22 colour normal observers (mean age 28 years) participated in the study.

Psychophysical procedure

Contrast matching was done across luminance levels. Each session consisted of test stimuli displayed at either 0.02, 0.2, 2, 20, 200, or 2000 cd/m^2 on the left (HDR display). The reference stimulus was displayed on the right (SDR display) at a mean luminance of 200 cd/m^2 for all the sessions. In low luminance test conditions (0.02, 0.2, and 2 cd/m^2) we allowed for a five minute dark adaptation period. The participants were asked to quickly alternate between the two eyes to ensure that both eyes were adapted to their respective luminance levels. Within each session, stimuli of all three spatial frequencies, three suprathreshold contrast levels, and all three chromatic directions were randomly interleaved. The test and reference stimuli were of identical spatial frequency and colour direction but rendered at different luminance luminances (except for the test = 200 cd/m^2 condition, which matched the reference luminance level). The contrast of the reference stimulus was fixed at any of the *high, medium*, and *low* reference contrast conditions, while the contrast of the test stimulus could be manipulated by the observer. The initial test contrast was assigned a random value that was either higher or lower than the reference contrast. The lower initial value was the threshold contrast of the corresponding stimulus, while the higher initial value was the highest contrast that the display was able to produce at that viewing condition.

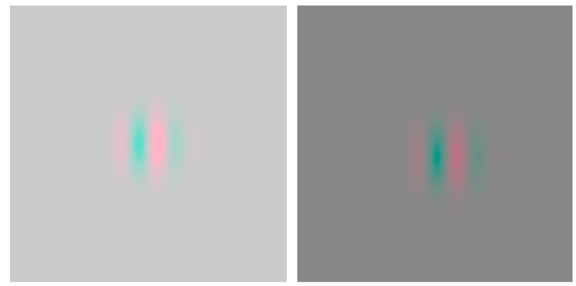

Figure 3. *An example contrast matching trial. The same stimulus is shown at two luminance levels and the observer is asked to adjust the contrast of the test stimulus until both stimuli have the same perceived contrast.*

We used the method of adjustment to measure the point of subjective equality between the test and reference contrast. The observers were asked to increase or decrease the test contrast until they perceive both stimuli as equal in contrast relative to their respective background luminances. Once the observers were satisfied with the match, they pressed a button and moved on to the next trial. For some extreme conditions where a match was not possible, the observers were able to skip to the next condition. Each pair of test and reference contrast was measured 3 to 5 times depending on the variance between measurements for each observer. The measurement of a condition was concluded when either the (within-observer) target standard deviation of 0.1 units was achieved or when the condition was measured 5 times.

Results and discussion

The mean results from all the observers are summarised in Figure 4. The three columns represent data from the three spatial frequencies. The rows represent the three colour directions. Each panel has three matching curves corresponding to *high, medium*, and *low* suprathreshold contrast conditions. For each suprathreshold matching curve, the corresponding reference contrast line is also shown. The grey dotted lines represent the contrast thresholds across luminance levels for the corresponding spatial frequency pattern from a prior work [8].

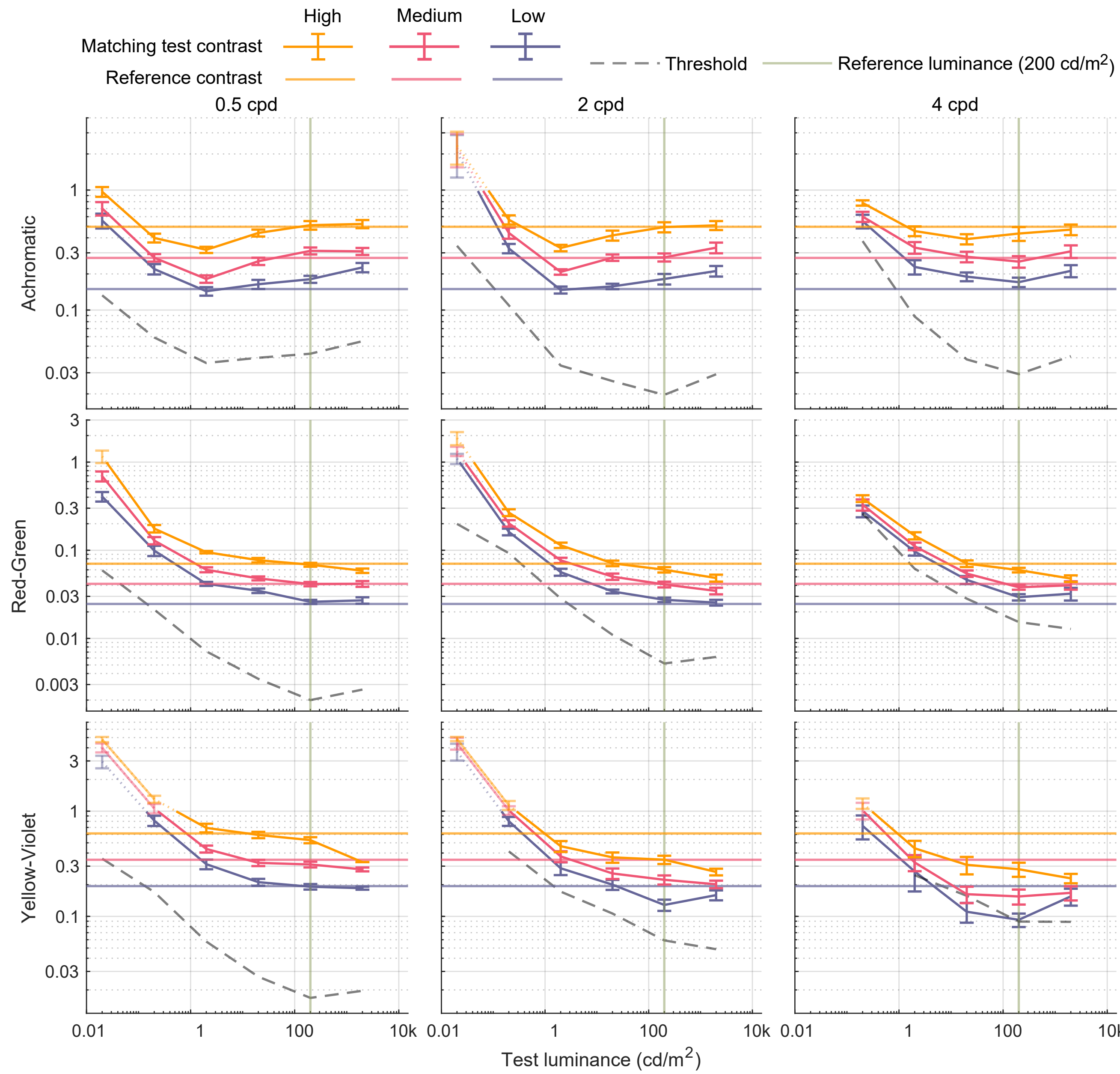

Figure 4. *Mean measurements for contrast matching across luminance levels for 22 observers. Error bars are $\pm SEM$ (standard error of mean). Fixed reference stimuli at 200 cd/m^2 are perceptually matched with equivalent test stimuli. The matching pairs span multiple spatial frequencies, colour directions and suprathreshold contrast levels and are presented at different luminance levels. The matched contrasts greater than 1 are denoted by dotted lines, since the stimuli become asymmetrical (in terms of contrast) once this limit is passed.*

To a first approximation, we can conclude that contrast constancy does not hold over large luminance ranges. This is apparent from the lines of matching test contrast from the figure, which deviate strongly from horizontal. If the phenomenon of contrast constancy was valid for matching across luminance levels, test contrasts magnitude would equal reference contrast magnitude regardless of the mean luminance. This is not the case in our measurements.

Although contrast constancy is not achieved for the full luminance range, we observe regions of constancy in the data. Between 20 - 2000 cd/m^2 we find approximate contrast constancy in most cases. For achromatic *medium* and *high* suprathreshold stimuli, the lines of matching contrast almost fully coincide with the reference contrast, indicating contrast constancy. This is also generally the case with red-green and yellow-violet stimuli at all three suprathreshold levels, with the exception of high spatial frequencies, for which the sensitivity is also lower.

For all conditions, the low luminance stimuli are matched at a much higher contrast compared to the reference. The findings are not surprising since our tested low luminance levels coincide with the DeVries-Rose region. But it also indicates that for matching across luminance levels, the factors that limit contrast sensitivity are not fully compensated for in the suprathreshold region. It should also be noted that the differences between reference and low luminance matched test contrast is much higher for red-green and yellow-violet stimuli. Chromatic mechanisms lose contrast sensitivity at a higher rate with decreasing luminance, and this continues to be the case at suprathreshold levels.

Low contrast suprathreshold stimuli show slightly different trends for the achromatic direction. For 0.5 and 2 cpd stimuli, the test contrasts at 2 and 20 cd/m^2 are matched well with the reference stimuli, while the higher photopic stimuli at 2000 cd/m^2 require higher contrasts to match with the reference. This resembles the trend in high luminance achromatic contrast sensitivity functions for lower sensitivity (i.e. increased threshold contrast) with increasing luminance beyond 200 cd/m^2. One explanation could be that since the *low* suprathreshold level is closer to the threshold, it is possible that the matching for these conditions is mediated by both threshold and suprathreshold physiological mechanisms. However, the same can not be said for chromatic stimuli. For both red-green and yellow-violet stimuli, despite increase in threshold at very high luminance level, no such increase in matched test contrast is observed even at *low* suprathreshold level.

The relationship between the threshold and suprathreshold matching curves is not a one-size-fits-all model. As shown in Figure 4, for the 0.5 cpd condition, the matching curves are separated from the threshold curves by an approximately constant offset (in log scale) across the whole luminance range. However, as spatial frequency increases, this log-offset relationship between threshold and matching curves no longer holds. To adequately characterise contrast matching across luminance levels, we need a more sophisticated model instead of simple threshold difference-based models [15].

Conclusions

Contrast constancy, a phenomenon that has been well-established for matching across spatial frequencies, does not hold true for matching across large luminance ranges. We showed that for a limited photopic range ($\sim$2 log units), magnitudes of matched contrasts are equal, but contrast constancy fails at mesopic lightness levels (below 2 cd/m^2) resulting in large differences between matched and reference contrast. Our work provides a large dataset for contrast matching for different spatial frequencies, suprathreshold levels and colour directions.

Our future work will be focused on modelling and verification of contrast matching functions across luminance levels for complex images. The model will be integrated into a retargeting framework that simulates and compensates for image appearances under different light conditions.

Acknowledgements

We would like to thank Minjung Kim and Kristof Santa for their help in data collection.

This research was funded by EPSRC grants EP/P007503, EP/P007910, EP/P007902, and EP/P007600. This project has also received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 725253–EyeCode).

References

[1] J. G. Robson, "Spatial and temporal contrast-sensitivity functions of the visual system," *Josa*, vol. 56, no. 8, pp. 1141–1142, 1966.

[2] F. W. Campbell and J. G. Robson, "Application of fourier analysis to the visibility of gratings," *The Journal of physiology*, vol. 197, no. 3, p. 551, 1968.

[3] D. Kelly, "Visual contrast sensitivity," *Optica Acta: International Journal of Optics*, vol. 24, no. 2, pp. 107–129, 1977.

[4] K. T. Mullen, "The contrast sensitivity of human colour vision to red-green and blue-yellow chromatic gratings.," *The Journal of physiology*, vol. 359, no. 1, pp. 381–400, 1985.

[5] J. M. Rovamo, M. I. Kankaanpää, and H. Kukkonen, "Modelling spatial contrast sensitivity functions for chromatic and luminance-modulated gratings," *Vision research*, vol. 39, no. 14, pp. 2387–2398, 1999.

[6] F. L. Van Nes and M. A. Bouman, "Spatial modulation transfer in the human eye," *JOSA*, vol. 57, no. 3, pp. 401–406, 1967.

[7] J. Mustonen, J. Rovamo, and R. Näsänen, "The effects of grating area and spatial frequency on contrast sensitivity as a function of light level," *Vision research*, vol. 33, no. 15, pp. 2065–2072, 1993.

[8] S. Wuerger, M. Ashraf, M. Kim, J. Martinovic, M. Pérez-Ortiz, and R. K. Mantiuk, "Spatio-chromatic contrast sensitivity under mesopic and photopic light levels," *Journal of Vision*, vol. 20, no. 4, pp. 23–23, 2020.

[9] J. G. Robson and N. Graham, "Probability summation and regional variation in contrast sensitivity across the visual field," *Vision research*, vol. 21, no. 3, pp. 409–418, 1981.

[10] S. J. Anderson, K. T. Mullen, and R. F. Hess, "Human peripheral spatial resolution for achromatic and chromatic stimuli: limits imposed by optical and retinal factors.," *The Journal of physiology*, vol. 442, no. 1, pp. 47–64, 1991.

[11] J. Rovamo, O. Luntinen, and R. Näsänen, "Modelling the dependence of contrast sensitivity on grating area and spatial frequency," *Vision research*, vol. 33, no. 18, pp. 2773–2788, 1993.

[12] C. Owsley, R. Sekuler, and D. Siemsen, "Contrast sensitivity throughout adulthood," *Vision research*, vol. 23, no. 7, pp. 689–699, 1983.

[13] M. Ashraf, S. Wuerger, M. Kim, J. Martinovic, and R. K. Mantiuk, "Spatio-chromatic contrast sensitivity across the lifespan: interactions between age and light level in high dynamic range," in *Color and Imaging Conference*, vol. 2020, pp. 65–69, Society for Imaging Science and Technology, 2020.

[14] M. Georgeson and G. Sullivan, "Contrast constancy: deblurring in human vision by spatial frequency channels.," *The Journal of physiology*, vol. 252, no. 3, pp. 627–656, 1975.

[15] J. Kulikowski, "Effective contrast constancy and linearity of contrast sensation," *Vision research*, vol. 16, no. 12, pp. 1419–1431, 1976.

[16] N. Brady and D. J. Field, "What's constant in contrast constancy? the effects of scaling on the perceived contrast of bandpass patterns," *Vision research*, vol. 35, no. 6, pp. 739–756, 1995.

[17] R. Hess, "The ed ridge-green lecture vision at low light levels: role of spatial, temporal and contrast filters," *Ophthalmic and physiological optics*, vol. 10, no. 4, pp. 351–359, 1990.

[18] E. Peli, J. Yang, R. Goldstein, and A. Reeves, "Effect of lumi-

nance on suprathreshold contrast perception," *JOSA A*, vol. 8, no. 8, pp. 1352–1359, 1991.

[19] R. Wanat and R. K. Mantiuk, "Simulating and compensating changes in appearance between day and night vision," *ACM Transactions on Graphics (TOG)*, vol. 33, no. 4, pp. 1–12, 2014.

[20] M. Rezagholizadeh, T. Akhavan, A. Soudi, H. Kaufmann, and J. J. Clark, "A retargeting approach for mesopic vision: simulation and compensation," *Electronic Imaging*, vol. 2016, no. 20, pp. 1–12, 2016.

[21] A. Watanabe, T. Mori, S. Nagata, and K. Hiwatashi, "Spatial sine-wave responses of the human visual system," *Vision Research*, vol. 8, no. 9, pp. 1245–1263, 1968.

[22] C. Blakemore, J. P. Muncey, and R. M. Ridley, "Stimulus specificity in the human visual system," *Vision research*, vol. 13, no. 10, pp. 1915–1931, 1973.

[23] E. Peli, "Suprathreshold contrast perception across differences in mean luminance: effects of stimulus size, dichoptic presentation, and length of adaptation," *JOSA A*, vol. 12, no. 5, pp. 817–823, 1995.

[24] E. Peli, L. Arend, and A. T. Labianca, "Contrast perception across changes in luminance and spatial frequency," *JOSA A*, vol. 13, no. 10, pp. 1953–1959, 1996.

[25] K. Tiippana, J. Rovamo, R. Näsänen, D. Whitaker, and P. Mäkelä, "Contrast matching across spatial frequencies for isoluminant chromatic gratings," *Vision Research*, vol. 40, no. 16, pp. 2159–2165, 2000.

[26] P. B. Delahunt, J. L. Hardy, K. Okajima, and J. S. Werner, "Senescence of spatial chromatic contrast sensitivity. ii. matching under natural viewing conditions," *JOSA A*, vol. 22, no. 1, pp. 60–67, 2005.

[27] J. Shin, N. Matsuki, H. Yaguchi, and S. Shioiri, "A color appearance model applicable in mesopic vision," *Optical review*, vol. 11, no. 4, pp. 272–278, 2004.