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Can ‘crispening’ be explained by contrast gain?

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Abstract

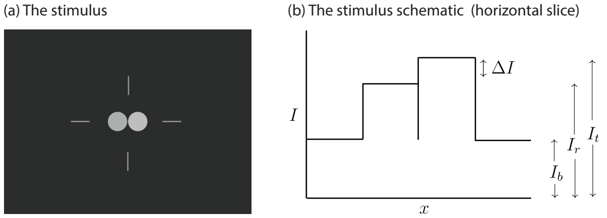
‘Crispening’ is an effect whereby subjects perception of luminance is biased away from the background luminance level. The effect is strong, but may be reduced or abolished by the addition of a hue shift or an annulus that separates the tests stimuli from the background [16, 18]. In this paper we investigate whether the ‘crispening’ effect may arise from a simple gain mechanism that decreases sensitivity at luminance levels away from the background luminance level. The model takes as input the threshold versus intensity function, then decreases sensitivity via a gain mechanism. The supra-threshold percept is then estimated via Fechnerian integration of the resulting thresholds. We find that the model can predict subjects’ luminance nonlinearities in all conditions as long as a parameter that controls the degree of gain is allowed to vary. Perhaps more interestingly, we find that the model can explain the luminance nonlinearity in the case where an annulus is present by treating the annulus as an additional background luminance level that also mediates gain. When multiple background luminance levels are included, the gain no longer produces the distinctive ‘crispening’ effect, although the gain still substantially affects the shape of the luminance nonlinearity. This may account for why ‘crispening’ is not observed when complex, real world scenes are investigated [2].

Introduction

The relationship between onscreen luminance and its subjective percept is not straightforward. For instance, the perceived lightness of a surface can change substantially depending on whether it is perceived to be in shadow or direct sunlight [1, 10]. Less intuitively, the perceived luminance of a surface in an image with no obvious three-dimensional structure can also vary considerably depending on the surrounding stimulus. Broadly speaking there are two types of lightness study, those that investigate the perceived lightness of two surfaces with a matched luminance but different surrounds and those that investigate lightness perception over a broad range of luminance levels. In this study we will focus on the latter and in particular on effect termed ‘crispening’ by Takasaki [15]. In figure 2b we illustrate two curves. The abscissa plots the onscreen luminance, normalised to between zero and one and the ordinate plots normalised lightness perception, with zero representing the percept of black, and one representing the percept of white. The cyan curve denotes a function that does not exhibit ‘crispening’. This function is compressive and the steepest gradient occurs at the lowest luminance level. In contrast the red curve illustrates a function with ‘crispening’. This function has a dramatically different shape and has two peaks in gradient, one at the lowest luminance level and another at the background luminance level.

‘Crispening’ is a strong effect which is observed in some studies [14, 15, 8, 18, 16], but not others [12, 2, 9]. The most thorough investigation of ‘crispening’ comes from two studies by Paul Whittle: The first investigated thresholds for the discrimination between the luminance of test and a reference luminance patch viewed upon a uniform background [16] and the second, supra-threshold lightness perception [18]. In the latter study subjects were asked to manipulate the luminance of a number of patches until they appeared to vary in a linear manner, from dark to bright. The patches were greyscale and the strongest ‘crispening’ effect was observed when the background luminance was also grey. The ‘crispening’ effect was reduced if the background and test stimuli had different hues (e.g. yellow test, grayscale background) and was nearly abolished when an annulus was added. The addition of a hue boundary or an annulus may serve to separate the test stimulus from the background and Whittle [18] speculated that the presence or absence of ‘crispening’ may be determined by high level feedback. We shall return to this point in the discussion.

The discrimination threshold study of Whittle can be described with the help of figure 1. Whittle investigated the minimum value of ΔI needed for reliable detection of an increment or decrement for different values of I_r and I_b. The study revealed threshold functions with the form depicted in 2a. The function has two peaks in sensitivity, one at the low luminance values and another at the background luminance level. Whittle demonstrated that the gradient of the supra-threshold functions could be superimposed upon the threshold functions, given an appropriate scaling factor (see figure 3 in [18]). Thus, to a high degree of approximation, Fechnerian integration of the discrimination threshold function can be used to estimate the supra-threshold percept. However, Whittle did not investigate whether discrimination thresholds could be used to predict functions that do not exhibit ‘crispening’. We shall return to this point in the discussion.


(a) The stimulus

(b) The stimulus schematic (horizontal slice)

Figure 1. *(a) Illustration of the stimulus used in a typical sensitivity experiment (b) horizontal slice of (a)*

Despite the strength of the ‘crispening’ effect illustrated in figure 2 its importance in determining the perception of complex real world scenes has not been established. There is reason to believe that the impact of ‘crispening’ may be limited. Importantly, the effect was not observed when Bartleson and Breneman [2] investigated brightness perception using real world scenes, and it is frequently not present in lightness studies using experimenter defined stimuli [12, 9]. This combined with the observation by

Whittle [18] that the effect may be reduced or abolished by an annulus or hue difference suggests the effect is brittle and thus easily abolished when complex stimulus are used.

Overview

This paper is set out in the following way: We begin by briefly reviewing the principle of Fechnerian integration and demonstrate how a threshold versus intensity (TvI) function, when modified by a gain control mechanism, may give rise to ‘crispening’. In the methods section we introduce two experiments: one to derive the TvI function and another to derive lightness functions. We then demonstrate how the experimentally obtained TvI function is required to obtain lightness functions that match those of our subjects. This is then followed by three supra-threshold experiments that investigate lightness perception for grey and green background conditions and with either a black or a white annulus.

Briefly, we use the term lightness rather than brightness in this paper as subjects are asked to manipulate a series of greyscale patches until they appear change in a linear manner from *black* to *white*, rather than from *dark* to *light*. As noted by Rudd [13], the term achromatic luminance perception is arguably more apt to use for these experiments and we do not distinguish between lightness and brightness perception.

A gain model of ‘crispening’

Fechner’s law states that the perceived stimulus magnitude is proportional to the integral of sensitivity along a given stimulus dimension (e.g. sound or luminance) [4]. This principle, if accepted, allows one to estimate the supra-threshold percept from objective measurements of sensitivity [18, 5]. The parameters for a simple sensitivity experiment are shown in figure 1. In the case where the reference and background have the same luminance ($I_r = I_b$) the task reduces to a detection task of a small flash on a uniform background. This function is commonly referred to as the TvI curve and under some conditions can be approximated by Weber’s law ($W = \Delta I/I$). In the case where Weber’s law holds true or approximately true then Fechner integration predicts a compressive function with the greatest sensitivity at the low luminance levels. Thus it is clear that Weber-like behaviour must be modified in some way to produce the ‘crispening’ effect. Whittle’s approach was to modify the Weber law such that $W = I_p/I_{min}$, where L_{min} is the minimum displayed luminance. In the case of increments $I_{min} = I_b$, but in the case of decrements $L_{min} = L_r$. This formulation was based on the observation that the modified W was now a linear predictor of the incremental and decremental thresholds obtained in [16].

In this paper we take a different approach: We assume the human visual system has a maximal sensitivity to luminance variations defined by the TvI function estimated when $L_r = L_b$ and postulate that deviations from the TvI curves when $I_r \neq I_b$ result from a gain control mechanism. The gain factor decreases sensitivity (increases thresholds) in linear proportion to the absolute difference between the background luminance and the test luminance level. Lightness can then be computed from the underlying thresholds via Fechner integration.

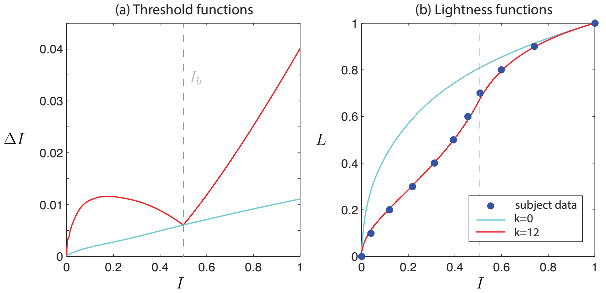


Figure 2. *(a) Thresholds ΔI as a function of the reference luminance I_r. The background luminance level I_b is illustrated by the vertical grey dashed line. The cyan line is for $k = 0$ and the red for $k = 12$ (see methods). (b) The supra-threshold percept obtained by Fechnerian integration of the threshold functions. The open circles denote an experimentally obtained lightness function*

More formally, the gain factor is described by equation 1, where I is the luminance value, I_b the background luminance and k a constant that determines the degree of ‘crispening’.

$$G_i = 1 + k|I_i - I_b| \tag{1}$$

τ is the TvI function for detection thresholds. This function can either be obtained experimentally or from the literature. Thresholds after the gain operation ΔI are then the product of τ and the gain G. Note that when $k = 0$, $\Delta I = \tau$.

$$\Delta I_i = \tau_i G_i \tag{2}$$

The stimulus magnitude at a given stimulus value is then.

$$M_i = \int_{I=0}^{I} \frac{1}{\Delta I_i} \tag{3}$$

Finally, M is divided by the maximum value of M to obtain a lightness estimate. A value of one thus indicates the percept of white.

$$L_i = \frac{M_i}{max(M)} \tag{4}$$

The impact of the parameter k on thresholds is shown in figure 2a and upon lightness perception in 2b. The impact is demonstrated for a stimulus with a mid-gay background luminance $I_b = 0.5$. If $k = 0$ then thresholds are equal to the TvI function and no ‘crispening’ is observed in either the threshold or the lightness function (cyan curves). To illustrate the impact of the gain term we plot the subjective data obtained when $I_b = 0.5$ using blue dots. This function exhibits strong ‘crispening’ and we get a good fit to this data (red curve) using $k = 12$. The discrimination thresholds shown in 2a for $k = 12$ approximately follow the form of the discrimination thresholds obtained by Whittle (figure 3, [18]). We reserve a quantitive evaluation of our model and that of Whittle upon the Whittle’s data for a later paper. However it is worth noting that for reference luminance levels greater than the background luminance level ($I_r > I_b$, referred to as incremental thresholds by Whittle), our model predicts a weak expansive function, whilst the model of Whittle predicts a linear function.

Methods

Apparatus

Stimuli were displayed on a Philips 109B CRT monitor with spatial and temporal resolutions of 1280 by 960 pixels and 75 Hz and a luminance range from 0.65 to 75 cdm^{-2} in a purpose built laboratory. The display was viewed at a distance of 58 cm so that 64 pixels subtended 1 degree of visual angle a chin rest was used to maintain a constant viewing position. The full display subtended 35.5° by 25.5°. Stimuli were generated on an Apple MacBook running MATLAB (MathWorks) with functions from the Psychtoolbox [3, 11]. On an individual frame only a limited number of luminance levels (a maximum of 14) where displayed, thus the color lookup table (CLUT) was dynamically updated on each frame to allow for an, in effect, continuous VGA signal to be sent to the monitor. The encoding gamma of the monitor was recorded with a Konica Minolta LS 100 photometer and corrected for.

Subjects

There were 8 participants in total, all with corrected to normal vision. 7 were naïve to the experimental objectives and one was the author. All subjects had corrected or normal vision. All procedures complied with the declaration of Helsinki and were approved by the Comité Ético de Investigación Clínica, Parc de Salut MAR, Barcelona, Spain.

Experiment: Threshold versus intensity function for detection

The stimulus for this experiment is illustrated in figure 1. Subjects viewed a uniform surface with luminance I_b. On each trial a 1° circle was presented for 75ms, the circle was either an increment or decrement. The circle was centrally presented with an offset of ±0.5° either to the left of right of fixation. The subjects task was to indicate with a key press which side of fixation the stimulus appeared. The centre of the screen was indicated by a cross-hatch. Each background luminance level was tested on a separate run. The luminance of the cross hatch was adjusted to be just visible before experimentation.

Procedure: Threshold versus intensity function for detection

In this experiment we investigated detection thresholds (i.e when $I_b = I_r$) as a function of the background luminance level I_b. Thresholds were estimated using the method of constant stimuli. Values of I_t that are both greater and less than I_b were tested such that we spanned the subject's full psychometric function (from 0 to 100% correct). A cumulative Gaussian is fit to the data and the standard deviations is used as the measure of sensitivity. We did search for an asymmetry between increments and decrements but did not find a systematic deviation. All reported thresholds are thus for the full psychometric function. For the purpose of the current study thresholds are obtained individually for each subject and averaged.

Experiment: Perceptual linearisation

Subjects viewed eleven uniform circles with a 1° diameter. The circles all lay upon the horizontal meridian of the monitor and were separated by 1° horizontal gaps. The leftmost circles were always black and the rightmost circles always white and the intermediary circles began with a random luminance value. The background luminance levels in experiment one were 9.5, 36.9 or 55.2 cdm^{-2} and the background was either grey or green. 55.2 cdm^{-2} corresponded to the maximum output of the green gun. Experiment 2 included the 0% and 100% grey background luminance levels. Experiment three had a background luminance of 50% or 48.5 cdm^{-2} and an annulus was added that subtended 0.125° and had a luminance of either a 0% and 100%.

Procedure: Perceptual linearisation

Each subject had to manipulate the luminance of the nine intermediary circles until they appeared to vary, from left to right, in a perceptually linear manner from black to white. The subject selected a circle via a the number key dedicated to that patch. The luminance could then be manipulated using the keys (**up**, **down**, **left**, **right**). The **up** and **down** keys produced positive or negative adjustments of 0.01. The left and right keys, 0.005. For greater sensitivity, the subjects could use the keys (**w**, **s**, **a**, **d**). The **w** and **s** keys produced positive or negative adjustments of 0.001, the **a** and **d** keys 0.0005. This was only needed when the background luminance was black. Subjects could produce a continuous adjustment by holding the respective key down. Subjects moved to the next conditions by pressing the **space** key. The luminance value obtained for each patch are averaged across subjects.

Results: Threshold versus intensity

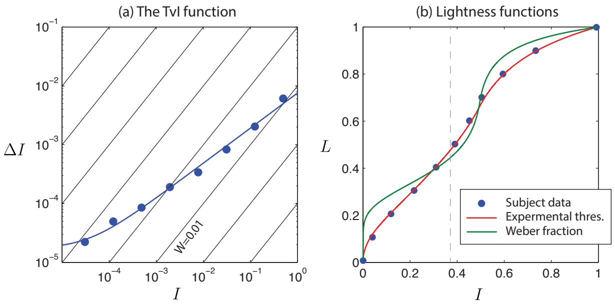


Figure 3. *(a) Threshold versus intensity (TvI) function for detection. The blue dots indicate the experimentally obtained thresholds and the solid blue line the best fitting equation (see main text). The diagonal lines indicate the predictions for a constant Weber fraction. A Weber fraction of 0.01 has been annotated. In relative terms, the experimental thresholds do not fall as quickly as predicted by Weber's law (b) The blue dots denote results an experimentally obtained lightness function for a uniform grey background with* $L_b = 38\%$. *The red curve denotes the best fitting lightness function when the experimentally obtained TvI curve is used and the green curve, when the TvI curve is modelled using a fixed weber fraction.*

The model developed in this paper takes as input a TvI function. In this section we investigate the impact of two TvI curves; one in which thresholds were proportional to intensity (Weber's law, $W = \Delta I/I$) and another that was obtained experimentally (see methods) and illustrated in figure 3a by a the blue curve. This continuous TvI has the form

$$\tau = a(I+d)^e \tag{5}$$

and the best fitting parameters are $a = 0.008$, $d = 4 * 10^{-}5$, $e = 0.6$. Clearly, this function does not exhibit a constant Weber fraction ($\Delta I \propto I$). However, in threshold versus intensity experiments, for detection thresholds, a fixed Weber is only ever approximately true for luminance values greater than 100 cdm^{-2} [7, 6], at lower values the Weber fraction varies inversely with luminance as observed in our data set.

The experimentally estimated function, or the Webber function could then be fed into the model to obtain lightness functions. The two resulting functions are shown in figure 3b and both were both fit to the experimental data obtained with a uniform grey background of $L_b = 0.38$ luminance and no annulus. The best fitting function obtained with the Weber law TvI is illustrated by the green curve ($k = 501$) and the function obtained with the experimentally estimated TvI function ($k = 11.6$) by the red curve. Clearly using the experimentally estimated TvI function produces a better fit. The reason for this is that the Weber law thresholds are relatively speaking much lower than the experimentally estimated thresholds at low luminance levels. As a result the suprathreshold function is too steep at low luminance levels and a good fit is impossible.

Results: Lightness functions

Green and grey background conditions

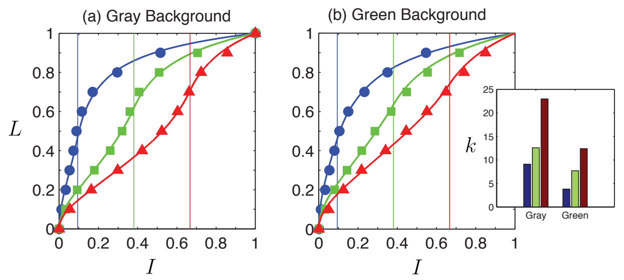


Figure 4. *(a) Lightness functions for three background luminance levels for grayscale backgrounds (b) Lightness functions when a green background is used. The green and grey background have matching intensities*

The results of the first lightness experiment are shown in figure 4. The experimental design was inspired by results from Whittle [18] who demonstrated that the 'crispening' effect was weaker when a hue difference was introduced between the test patches and the background. This was done by using yellow test stimuli viewed upon a background with either a red or a green hue. This was done for a single background luminance level. In this experiment we use three grey and green background luminance levels. To allow direct comparison of the function we match the luminance levels of the green and grey backgrounds. The maximal grey level tested corresponds to the monitor luminance when the maximum pure green stimulus is presented. The other two conditions correspond to 66% and 33% of this value. The open circles correspond to the subjects' average data and the solid lines the best fitting results from our model. The best fitting values of k are shown in the inset. Overall, the model produces satisfactory fits to the experimental data and two patterns can be observed in the best-fitting values of k. First, k increases with the background luminance level and second, the value is lower in the green condition. The ratio of k for the grey and green backgrounds is relatively constant at (2.39, 1.64, 1.85). A direct comparison with the experiments by Whittle is not possible as different luminance levels are used. However, from inspection it would appear that the greater hue manipulation of Whittle (yellow to red rather than grey to green) causes a greater reduction in the 'crispening' effect than we observe here.

From black to white background luminance levels

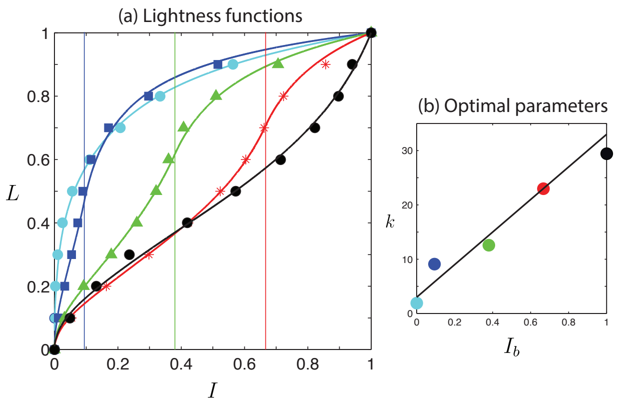


Figure 5. *(a) Lightness functions for five grey background luminance conditions, the background luminance is indicated by the vertical line except for the cyan and black curves which are respectively for the black and white background luminance conditions. (b) The best fitting values of the 'crispening' constants k.*

To understand more fully how k varies with the background luminance level we tested the 0% and 100% background luminance levels. The resulting lightness functions are shown in figure 5a along with the previous three backgrounds levels obtained in the previous experiment. In figure 5b we plot the optimal values of k as a function of the relative background luminance level and find a linear relationship. We model the relationship using the linear function $k = mL_b + c$ and find that best fitting values are $m = 30$ and $c = 3$. The non-zero value of c when $L_b = 0$ indicates that 'crispening' is always needed to fit the curves accurately.

The overall impact of a value of $k > 0$ when $I_b = 0$ is to steepen the slope at low luminance values. This is somewhat counterintuitive given that our gain model increases thresholds. However, after the normalisation of the lightness function it is true to say the function is relatively more steep at low luminance values than would be the case if $k = 0$.

Adding An Annulus

Whittle observed that the 'crispening' effect was greatly reduced or abolished by the addition of an annulus separating the test stimuli from the background. To investigate this we set the background luminance to 50% and tested under three conditions: no annulus, a black annulus and a white annulus. The results are shown in figure 6. In the no annulus condition 'crispening' is clearly apparent and the gradient of the function is very steep around the background luminance level, however in the black and white annulus conditions 'crispening' is not obviously apparent. Overall the function is more compressive when the black annulus is used and less compressive when the white annulus is used. This led to the hypothesis that these functions might be produced by gain from both the annulus luminance and the background luminance levels. To test this simple hypothesis we extend the model

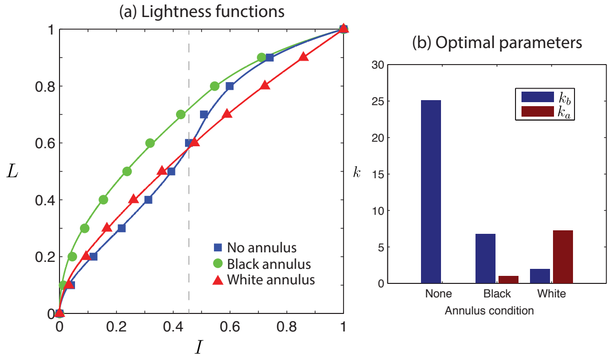


Figure 6. *(a) Lightness functions for three conditions with a 50% background luminance. Blue, no annulus, green, black annulus and red, white annulus (b) the best fitting ‘crispening’ constants.*

the gain equation to include a new gain term determined by the luminance of the annulus I_a.

$$\Delta I_i = \tau_i(1 + k_b|I_i - I_b|)(1 + k_a|I_i - I_a|) \qquad (6)$$

We now have two ‘crispening’ constants k_b and k_a for the background and annulus respectively. This extension of the model allows for satisfactory fits to the lightness functions. Interestingly, when multiple gain terms are used, the impact of gain does not produce an obvious ’crispening’ effect around the background luminance level. In large part this is because the value of k_b is much lower than the value obtained in the no-annulus condition, but additionally because the multiple gain functions are in operation thus making the impact of each individual one less obvious.

Discussion

In this paper we demonstrate how a simple gain mechanism can cause the ‘crispening’ effect. This work is at an early stage and two additional articles are being written: The first will include a explicit comparison of Whittle’s model against ours upon the data from both Whittle’s threshold [16] and the supra-threshold [18] studies. The second article will expand upon this work to include a number of additional background luminance conditions and attempt to formulate a general model for the parameter k.

One of the main contributions of Whittle’s work was to demonstrate that discrimination thresholds ($I_b \neq I_r$) rather than detection thresholds ($I_b = I_r$) could be used to predict the supra-threshold percept of luminance. However this finding was only demonstrated for functions that exhibit ‘crispening’ and not the more common compressive form, with only one peak in gradient at the low luminance levels. This is critical because the majority of lightness functions exhibit this form, including those established using real world scenes [2].

The contribution of this paper is to explicitly formulate ‘crispening’ as an effect mediated by gain. Within this model gain is mediated upon the test stimuli by the background luminance level or levels. By modulating the degree of gain and the number of background luminance levels a broad set of functions can be produced. The impact of gain is best illustrated in the case of a uniform background condition with a mid-grey luminance level. If the gain is zero then the lightness function is simply the integral of the TvI function for detection thresholds. If the gain is strong, then the ‘crispening’ effect is produced. Thus this model can predict both functions that exhibit and do not exhibit ‘crispening’ and strengthens the argument that discrimination thresholds rather than detection thresholds should be used to infer the supra-threshold percept. In the case of the annulus conditions, we extend the model such that the luminance of both the background and the annulus mediate the overall gain. This approach offers the possibility of extending the model to more complex stimulus classes. A key point to note is that as the number of background luminance levels increases, the gain still affects the shape of the luminance nonlinearity, but does not produce the distinctive ‘crispening’ shape. This offers a potential explanation for why the ‘crispening’ effect is not observed when complex, real world scenes are used [2]. An additional contribution is that the impact of adding a hue difference or an annulus can potentially be explained by a simple low-level mechanism without explicit reference to a high level system that mediates the ‘parsing of illumination and reflectances in complex scenes’ as suggested by Whittle [18, 17]. However, if the model is to be more than a convenient way to describe the data, a general model of how k varies with the background condition must be developed and evaluated.

In combination with Whittle’s earlier studies [16, 18] the theory developed here provides the intriguing possibility that discrimination thresholds can be used to develop a general model of lightness perception. An obvious theoretical advantage of using a discrimination paradigm over a detection paradigm is that thresholds can be obtained over a broad range of reference luminance values whilst maintaining a fixed background luminance level. As the background luminance level primarily determines the overall light level the adaptation condition will vary less than in an study of detection thresholds over the same luminacne range. Given that the supra-threshold percept is normally evaluated using a fixed overall light level, Fechnerian integration of discrimination thresholds should be more appropriate than Fechnerian integration of detection thresholds. The advantage of integrating over detection thresholds is that the TvI function has long been established over a very broad range of luminance values [6] and the approach has recently proven useful in the development of an encoding nonlinearity for high dynamic range monitors [7] which was demonstrated to reduce the visibility of quantisation errors. However, the approach can only produce one function for a given luminance range and thus cannot account for how the visual system adapts to other stimulus dimensions such as the luminance distribution of the scene [12] or the impact of the surround luminance [2]. As such the theory developed may be of interest to those in the Electronic Imaging community.

Acknowledgements

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Author Biography

David Kane received his PhD from University College London where he developed a grounding in basic psychophysics. From there David pursued an interest in working at the intersection of perception and technology and worked with Professor Marty Banks at The University of California, Berkeley working on issues surrounding stereo 3D displays. Currently, David is working as an in-house experimental psychologist in the image processing lab Marcelo Bertalmío at Universitat Pompeu Fabra.

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