A multi-scale Gaussian filtering model to explain the White's illusion from the viewpoint of lightness assimilation for widely varying grating width and patch length

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The variation between the actual and perceived lightness of a stimulus has strong dependency on its background, a phenomena commonly known as lightness induction in the literature of visual neuroscience and psychology. For instance, a gray patch may perceptually appear to be darker in a background while it looks brighter when the background is reversed. In the literature it is further reported that such variation can take place in two possible ways. In case of stimulus like the Simultaneous Brightness Contrast (SBC), the apparent lightness changes in the direction opposite to that of the background lightness, a phenomenon often referred to as lightness contrast, while in the others like pincushion or checkerboard illusion it occurs opposite to that, and known as lightness assimilation. The White's illusion is a typical one which according to many, does not completely conform to any of these two processes. This paper presents the result of quantification of the perceptual strength of the White's illusion as a function of the width of the background square grating as well as the length of the gray patch. A linear filter model is further proposed to simulate the possible neurophysiological phenomena responsible for this particular visual experience. The model assumes that for the White's illusion, where the edges are strong and quite a few, i.e. the spectrum is rich in high frequency components, the inhibitory surround in the classical Difference-of-Gaussians (DoG) filter gets suppressed, and the filter essentially reduces to a multi-scale Gaussian kernel that brings about lightness assimilation. The linear filter model with a Gaussian kernel is used to simulate the White's illusion phenomena with wide variation of spatial frequency of the background grating as well as the length of the gray patch. The appropriateness of the model is presented through simulation results, which are highly tuned to the present as well as earlier psychometric results.

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Abstract

The variation between the actual and perceived lightness of a stimulus has strong dependency on its background, a phenomena commonly known as lightness induction in the literature of visual neuroscience and psychology. For instance, a gray patch may perceptually appear to be darker in a background while it looks brighter when the background is reversed. In the literature it is further reported that such variation can take place in two possible ways. In case of stimulus like the Simultaneous Brightness Contrast (SBC), the apparent lightness changes in the direction opposite to that of the background lightness, a phenomenon often referred to as lightness contrast, while in the others like pincushion or checkerboard illusion it occurs opposite to that, and known as lightness assimilation. The White's illusion is a typical one which according to many, does not completely conform to any of these two processes. This paper presents the result of quantification of the perceptual strength of the White's illusion as a function of the width of the background square grating as well as the length of the gray patch. A linear filter model is further proposed to simulate the possible neurophysiological phenomena responsible for this particular visual experience. The model assumes that for the White's illusion, where the edges are strong and quite a few, i.e. the spectrum is rich in high frequency components, the inhibitory surround in the classical Difference-of-Gaussians (DoG) filter gets suppressed, and the filter essentially reduces to a multi-scale Gaussian kernel that brings about lightness assimilation. The linear filter model with a Gaussian kernel is used to simulate the White's illusion phenomena with wide variation of spatial frequency of the background grating as well as the length of the gray patch. The appropriateness of the model is presented through simulation results, which are highly tuned to the present as well as earlier psychometric results.

Keywords: brightness induction, spatial filter, surround suppression

Introduction

Studies of visual illusions generally provide some new insight into the understanding of the process of visual perception in the human brain. The literature describing the illusory visual phenomena with qualitative as well as quantitative analysis is quite rich and of particular interest is a class of stimuli often called the brightness/lightness perception illusions. Following the footprints of one recent paper (Shi et al., 2013) which in turn attempt to advance an earlier work by Troncoso et al.(2005), we undertake an experiment on such a well-known brightness illusion, known as the "White's Illusion" (White, 1979). White's illusion stimuli of achromatic as well as pan-chromatic nature have been studied by various researchers. Chromatic prototypes of almost identical illusions were designed much earlier by Munker (1970) and Gindy (1963). The study reported in the present paper is confined to the achromatic version. White's Illusion, according to its author (White, 2010) is one of the strongest lightness illusions. The term "lightness" merits some discussion. Appearance of an object to the Human Visual System (HVS) depends not only on the luminance (luminous intensity over a given area and direction) but also on the reflectance of the object. Brightness is defined as the "apparent luminance", while lightness is termed as the "apparent reflectance". Brightness ranges from "dim" to "bright", and lightness ranges from "dark" to "light". It is worth mentioning here that in the present paper "lightness" refers to achromatic gray values ranging black to white, and even if the term perceived brightness occurs in comparison to darkness, it is meant to refer to lightness only, as explained above.

Figure 1: The White's illusion (1979)

Figure 1 represents a typical pattern of White's illusion (White, 1981). The gray patches on the black bars appear lighter than the identical gray patches on the white bars in spite of being exactly identical with respect to their intensity values. It can be noted that in this illusion, the gray target that appears darker are bordered by more black than white, and the targets that appear lighter are bordered by more white than black, and this in fact happens independent of the aspect ratio of the targets.

Many visual illusions like the Simultaneous Brightness Contrast (SBC) are explained with the help a concept called *lateral inhibition* (LI), which arose from the pioneering description of the center-surround receptive field (RF) in mammalian retina by Kuffler (1953). Here one assumes that the stimulus generated through the cells of the central region of the RF is inhibited by the cells of the peripheral region of the RF. The concept was further experimentally corroborated by Hubel & Wiesel (1962) and subsequently refined through the theoretical models like 'Difference of Gaussians' or DOG (Rodieck and Stone,1965) and 'Laplacian of Gaussian' or LOG (Marr, 1982). According to LI, a gray patch surrounded by a dark region appears lighter to HVS than an identical patch surrounded by white region. White's illusion obviously exhibits properties contrary to the concept of LI. Hence from the very beginning, alternative models were sought to explain the phenomenon. A strong contender to LI is the supposed process of assimilation, in which it is assumed that in HVS there is a tendency to perceive the objects in the lightness of their surroundings. A well- studied example of lightness assimilation is the pincushion image stimulus shown in Figure 2 as reproduced from de Warrt and Spillmann (1995). Thus a gray object on a dark background appears darker than an identical object in the white background. While the process of LI is subtractive, the process of assimilation is additive. It is further conjectured that LI is computed at the retinal level, while the process of assimilation is accomplished at the cortical level. Clearly, for Figure 1 LI is inapplicable as we see that the gray target that appears darker is bordered by more black than white. So is it a case of assimilation of lightness? Figure 1 seems to indicate the same. However, according to many researchers an interesting aspect of

Figure 2: The pincushion stimulus adopted from de Waart and Spillmann (1995) with arrows showing the effect of assimilation of lightness from the white and black inducing rings a phenomenon that occurs irrespective of the thickness of the rings in this figure.

the White's illusion is that it does not completely conform either to the process of lateral inhibition or to the process of assimilation. This they conclude because the White's illusion occurs irrespective of the aspect ratio of the test patches in Figure 1, which means that although it so occurs that with respect to the two flanking bars, the lightness of the column on which the test patch is located becomes dominating beyond a certain aspect ratio as is evident from Figure 3 and Figure 4, still the direction of lightness induction does not change in such a situation. This means that while for vertically longer test patches theory of assimilation should work, it fails for the shorter ones when they are horizontally longer. However, this argument against lightness assimilation may not hold water if we consider larger receptive fields spanning the distant columns of the grating as well. However before we discuss more on this issue, let us first briefly review the previous records of the experimental follow-ups on White's illusion.

In White's illusion, the apparent lightness of the central gray patch changes with the width of the background grating or in other words with spatial frequency as shown in Figure 3.

Figure 3: White's illusion at 5 different grating widths

Anstis (2005) et.al. reported their results using a matching method on the variation of the apparent luminance as a function of the frequency of the background grating. The experimental procedure reported is as follows. Separated from the grating area of White's illusion, a gray patch was adjusted for the perceptual matching. The experiment was performed at five different spatial frequencies, starting from 0.627 cpd to 7.53 cpd (the unit cpd means cycles per degree of visual angle). The width of the gray test patch also is adjusted accordingly. As the spatial frequency was increased, the apparently lighter patch looked progressively even lighter and the apparently darker patch looked progressively even darker. At the highest spatial frequency, one of the test patches looked 2.5 times lighter than the other patch. Similar results were also obtained for the standard White's illusion by Blakeslee and McCourt (2004) which they then fitted with their proposed Oriented Difference of Gaussian (ODOG) model. In our present work we have varied the aspect ratio both by changing the spatial frequency of the grating, i.e. varying its width, as well as by altering the height of the test patch. We noted that Blakeslee and McCourt (2004) performed the experiments only for moderate values of the test patch height, and that Bakshi et al. have already shown (2015) that the ODOG spatial filtering model of Blakeslee and McCourt (2004) actually fails beyond such moderate range of test patch heights, i.e. for higher values. Hence we have performed our experiments as well as simulations for a large range, including those high values where the ODOG model fails, and tested our proposed assimilation based multi-scale Gaussian filter for that entire range. So alongside spatial frequency variance, the variation of the degree of apparent luminance based on the change in length of the test patch is

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an important subject studied in the present paper. White's illusion at 0.738 cpd and varying gray patch length is shown in Figure 4. It is observed that apparent lightness of the gray patch remains more or less constant.

Figure 4: White's illusion at 10 different gray patch length for spatial frequency 0.738 cpd

As has been mentioned, this type of study has already been undertaken by Bakshi et.al (2015), where the apparent lightness of a gray patch on coaxial white and dark bars are observed experimentally at a constant frequency of 0.40 cpd. The result of the psychophysical experiment showed that the apparent lightness remains almost constant for the length variation from 0.50 to 10 cpd.

Researchers have reported a few other experimental findings too concerning White's illusion. Apparently, for this effect the direction of brightness induction appears to follow the direction of assimilation, rather than contrast (Figure 1). However, Kingdom and Moulden (1991) have demonstrated with three inducing bars of varying width and a single gray test patch of variable height, that assimilation is not an important component of this illusion. Blakeslee et al. (2016) have also demonstrated similar experiments recently to arrive at similar conclusions. We have performed analogous experiments too, but unlike their cases, our White's stimulus has not been restricted to three inducing bars only. Hence, we refrain from rejecting the assimilation theory for White's effect, and have in effect proposed a new assimilation model based on multiscale Gaussian weighted spatial filters. For this, we have taken cue from Arend et al. (1971) who pointed out that for complex visual stimuli, contrast borders which are quite a distance away from each other to modulate local retinal mechanisms, may significantly, however, affect the brightness sensation through long distance integrations leading to assimilation. We considered the White's effect stimulus in this light as a much complex stimulus as compared to the SBC, with several contrast borders in the background of the test patches, rather than as the influence of only two flanking bars on either side of the test patch column as considered by Kingdom and Moulden (1991) and Blakeslee et al. (2016).

At this juncture we study the properties of the White's illusion first by varying the spatial frequency of the background grating and then varying the length of the gray patches under scrutiny. The Gaussian kernel filter model is also used to fit the psychometric test data with the simulation. Wide variation in spatial frequency and length of the gray patch is used to prove the appropriateness of the model and its generalized characteristics in the context of White's illusion.

Materials and Methods

The experimental results reported in the present paper consists of two sets of data. In the first set, spatial frequency have been varied from 3.67 cpd to 0.368 cpd, whereas the gray patch length has been kept constant at 70 pixels. In the second set of data the length of the gray patch has been varied from 16 pixels to 2 pixels by keeping the spatial frequency constant at 1.46 cpd and 0.738 cpd respectively. In both the cases psychometric experiments have been conducted with six subjects including three adult males and three adult females. Four of the subjects were naïve while the remaining two subjects were chosen from among the authors. In the first set, each experimental session was of duration 30 minutes and 5 such sessions completes a full cycle of experiment. Written consent was obtained from all subjects and the experiments have been approved by Scientific and Technical Advisory Committee (STAC), C-DAC. In the following we present the experimental arrangement and the results of the psychometric test with stimuli of spatial frequency variation and the variation of the length of the gray patch in two separate sections.

Psychometric Test for the White's Illusion stimuli with different spatial frequencies of the background grating:

The experimental arrangements were designed identical to that described in Shi et al. (2013) and Troncoso et al. (2005). A chinrest was placed 57 cm away from a linearized video monitor (HP Compaq LE 2002X with resolution 1024 x 1024 pixels). During the experiment, subjects rested their heads on it and viewed all the screen images (stimuli) binocularly. Two-alternative forced-choice (2AFC) paradigm, introduced by Fechner in 1889, was used in these lightness discrimination experiments. Visual comparisons between the lightness of a White's Illusion stimuli (comparator stimuli) and a graded gray patch (standard stimuli) pasted on a 50% gray background of uniform intensity 128, as shown in Figure 5(a), were conducted by different subjects. At the beginning of each trial, the subject was instructed to fix attention on a central red cross (1° within a 3.5° fixation window). After a lapse of 1 second, two sets of stimuli (comparator and standard) appeared on the screen simultaneously. One of them was centered at 7° to the left while the other centered at 7° to the right of the central cross.

Figure 5 : (a) Screen design of the psychophysical experiment, (b) Three different stimulus presentations of the lightness discrimination experiment

The White's Illusion stimulus (henceforth to be called as a comparator) was a grating of black and white stripes, in which a portion was partially replaced by a uniform gray rectangle as shown in Figure 1. While designing the stimulus, a relative scale of intensity was considered, in which, the intensity of the black stripe was 0%, while that of white stripe and the uniform rectangle were 100% and 50% respectively. In absolute scale, the intensity of the black stripe, white stripe and uniform gray rectangles were 0, 256 and 128 respectively. Within the comparator, the perceived lightness of the gray rectangles were strongly influenced by the lightness of the co-axial bars. It should be further noted that the width of the co-axial bars also had strong influence in modulating the perceived lightness of the gray rectangles. Five possible widths of the bars (3.67 cpd, 1.46 cpd, 0.738 cpd, 0.493 cpd and 0.368 cpd) were considered in our experiment. For the smallest width i.e. 3.67 cpd, eleven number of bars could be accommodated within the stimulus, whereas for the largest width i.e. 0.368 cpd, the number of bars had to be reduced to 5. This variation in the number of bars had been done to ensure that the region of comparison always be within 7° around the central cross mark.

The standard stripe on the other hand was divided into 11 segments of varying intensity. The relative luminance of these segments were categorized as 5%, 14%, 23%, 41%, 50%, 59%, 68%, 77%, 86% and 95%. The corresponding intensity values were 11, 23, 36, 59, 82, 105, 128, 150, 173, 196, 219 and 242 respectively. The order of appearance of these 11 segments within the standard bars was scrambled pseudo-randomly. Both the stimuli, i.e. the comparator and the standard, subtended 21° vertically. Two red vertical indicator lines were displayed 6° from the top and the bottom end of both the standard and the comparator, in order to confine the attention of the subject within the specific region of the stimuli to be compared. This is shown pictorially in Figure 5(b) for three different cases. As explained above, the vertical red-lines could select any one of the 11 segments in the standard stripe pseudo-randomly with equal probability. It is to be noted further that the red-lines were always aligned with the centre of one of the luminance segments.

The subjects were allowed to be accustomed with the arrangement for a brief period of time. The stimuli appeared on the display for 3 seconds and then disappeared. The subjects had to give their judgments within this period using two keys from the keyboard. Following 2AFC protocol, if the comparator appeared to be lighter than the standard, the subjects had to press key number one, otherwise they had to press key number two.

Subjects need not had to wait till the stimuli disappeared from the display, rather they were free to give their judgment as soon as they felt confident. One after another such pairs of stimuli appeared on the display for a duration of 3 seconds and the subjects had to compare the lightness of the comparator stimulus with that of the standard stimulus, which were always positioned exactly at the centre between the inner edges of the red-line markers.

In this process a particular region of interest in the comparator was judged against the parallel segment of the standard. The random choice of the selection of the region of interest ensured unbiased and uniform probability distribution. The difference of luminance between the comparator and the standard, as judged by the subject, is a function of the luminance of the segment within the standard stimulus at the point of comparison. In reality there exists no difference in the luminance of the co-occurring comparator and the standard. Therefore the apparent appearance of the segment of the comparator to be lighter or darker than that of the corresponding segment of the standard is entirely due to the psychophysical effect.

To keep the subjects unbiased, alert and attentive and also to avoid the fatigue during the experiments, various parameters were randomly changed during the display. A number of criteria were used in designing the experimental session as listed below:

(a) The subjects were exposed to a light appearing comparator (co-axial black region) in one half of the trials and a dark appearing comparator (co-axial white region) in the other half of the trials.
(b) The comparator appeared half the time on the left and half the time on the right of the standard during a complete session.
(c) The fixation marker was presented half the time on the top of the screen and half the time at the bottom of the screen randomly
(d) These occur with equal probability.

Several such stimuli are shown in Figure 5(b). Five experimental sub-sessions completed the full cycle of a session. Throughout a session, the grating frequency of the comparator remained constant. Each subject participated in 5 experimental sessions. The widths of the comparator black and white stripes are designed as 3.67 cpd, 1.46 cpd, 0.738 cpd, 0.493 cpd and 0.368 cpd. A complete session consisted of 150 trials and in each trial, the subjects recorded his/her judgment. The values of the parameters used to introduce variations in designing the stimuli are listed below in a tabular form in Table 1.

Table 1: Specification of the parameters of the test pattern used in psychometric test

Psychometric Test for White's Illusion stimuli with varying length of the gray patch

For quantifying the illusory effect of White's illusion, with variation of the test patch length, at a particular spatial frequency, similar psychophysical experiments have been conducted. The subject group consists of six subjects including three adult males and three adult females. Each experimental session was of duration 20 minutes and four such sessions were required to complete a full cycle of experiment by any subject. Written consent were obtained from all the subjects.

The arrangement of the experiments are similar as detailed in the previous experiment. This experiment has two parts. In the first part, the grating spatial frequency was kept constant at 1.46 cpd throughout the experiment, and for the second part it was kept constant at 0.738 cpd. The lengths of gray patch (comparator stimuli) were varied and were kept as 16 pixels, 8 pixels, 4 pixels and 2 pixels during one session. The subject had to compare between the lightness of the stimuli and a graded gray patch (standard stimuli), in a similar way mentioned in previous experiment. The subjects had to give their judgments following 2AFC protocol. If the comparator appeared to be lighter than the standard, subjects had to press key number one, otherwise they had to press key number two. Four experimental sub-sessions completed the full cycle of a session by a subject.

The proposed multi scale Gaussian kernel linear filter model of the receptive field for predicting White's illusion through brightness assimilation

Brightness assimilation has been studied for a long time. Helson (1963) for example, established that for the induction produced in the lightness of a gray background under the influence of black and white lines, assimilation may replace contrast as a function of the line width, line separation etc. Beck (1966) further substantiated by including top-down mechanisms into the theory of assimilation. He pointed out to the influence of these top-down factors in brightness assimilation, starting from the direction of intensity difference to even the experience of the observers. However, in spite of such rich studies on the mechanism of assimilation, very few theories have been constructed to explain a brightness perception phenomenon through assimilation mechanism. In the book *From Pigments to Perception* there is a chapter titled *Assimilation versus Contrast* written by CMM de Weert (de Weert, 1991) in which the author makes some profound statements in this context. For instance, he says that: *The mechanism of lateral inhibition is such a convenient mechanism and fits so well with contrast phenomena that acceptance of a second, perhaps simpler, mechanism (integration) only complicates our view of the system.* To account for such possible neuronal spatial integration within the receptive field, de Weert (1991) thus proposed large receptive fields without center-surround antagonism. Some others like Reid and Shapley (1988) have hinted at the possibility of such integration through weighted averages across distances in the visual cortex. The question therefore is that what can be an appropriate linear filtering model for lightness assimilation and whether such a model is applicable for explaining the White's illusion.

The linear filter model of different visual phenomena is a well-established branch of psychophysics. Cellular connectionist model based on classical receptive field and the lateral inhibitory process have already been used in developing model for various visual phenomena associated with lightness illusions (Macknik et al., 2000; Troncoso et al. 2005; Troncoso et. al., 2007; Troncoso et al. 2009). In the literature, the Difference of Gaussian function (DoG) is also well accepted as a linear filtering model of the classical receptive field in different layers of the visual pathway. All the visual phenomena associated with the size of test patches in simultaneous contrast (SBC) illusion have already been explained using DoG based simulation (Shi et al., 2013). However, the same type of simulation is either found inappropriate in case of White's Illusion or, there is unavailability of simulation result in case of White's Illusion stimuli having different grating frequency. In DoG model, the kernel of the filter is represented by the difference between the excitatory centre and the inhibitory surround, given as:

Receptive-field(x,y) = Centre(x,y) – Surround (x,y)

$$= \frac{k_c}{\sqrt{2\Pi\sigma_c^2}} e^{-[x^2+y^2]/2\sigma_c^2} - \frac{k_s}{\sqrt{2\Pi\sigma_s^2}} e^{-[x^2+y^2]/2\sigma_s^2}$$

There are four free parameters in the expression of the DoG kernel. σ_c and σ_s are the space constants of the Gaussians representing the centre and the surrounds, while k_c and k_s are the excitatory and inhibitory gain, respectively. In our simulation, these are set as (i)σ_c =0.8, σ_s= 5, k_c = 1, k_s =0.8 (ii) σ_c =2, σ_s= 4, $k_c = k_s$ =1, and (iii) σ_c =0.8, σ_s= 5, k_c = 1, k_s =0.25. Thus five stimuli representing White's illusion of different widths are prepared and they are convolved with DoG having different free parameters. For biological relevance, generally, we take center-width less than the surround-width and excitatory-gain greater than the inhibitory-gain. In the present model the same properties are preserved. However, as in Shi et al. (2013), we have, for the sake of mathematical exploration, also considered one case where the peak sensitivities (i.e. $k_c$and k_s) are equal. Thus the DoG filter effectively behaves as a derivative filter that enhances the contrast of the signal.

In the light of the above, we propose as an explanation to White's illusion, in the light of de Weert (de Weert, 1991), that as opposed to derivative filters, the mechanism of integration occurs over large receptive fields without center-surround antagonism in the form of the central Gaussian filtering. We have, therefore, tried to simulate the effects of White's illusion with a single, but multi-scale excitatory Gaussian filter. In the following we present the result of simulation using the Gaussian kernel of appropriate scale factor. The simulation is performed on two sets of stimuli. In one set, the length of the gray patch is kept constant while the spatial frequency of the background grating is varied. In the other set, the spatial frequency of the background grating is fixed while the length of the gray patch is varied. In choosing the space constant, we observe that the value of the appropriate σ_c depends on the spatial frequencies of the background grating in the first case and on the length of the gray patch in the second case. The results of simulation for different stimuli are presented in the following section.

Results

The simulation result presented in the following are the result of convolution of the Gaussian filter with two sets of stimuli, namely, White's illusion with varying spatial frequency and the same with varying length of the gray patch.

White's Illusion stimuli with different spatial frequencies

In the current experiment, following 2AFC protocol, stimuli are generated following the steps given above and the subjects are asked to indicate one of the two choices (either by pressing key number one when comparator appears to have different intensity than the standard or by pressing key number two otherwise) in response to those stimuli. Such experiments essentially determine the subjective response thresholds of the performers of the experiments, which are essentially the comparator intensities required to produce a given level of performance. Performance of the subjects improves as the comparator intensity is kept more and more away from the intensity of the standard. These experiments also record the rate at which the performance is improved. Purpose of these experiments is to measure two main parameters, namely: "point of subjective equality" (PSE) i.e. when the intensities of the comparator and the standard appear to be same to the subject and the subjective ability to discriminate between the intensities of the comparator and the standard. The former is known as "bias", while the latter is known as "discrimination ability".

Psychometric curves, given in Figure 6(a) are obtained by fitting the data with logistic functions using a maximum likelihood procedure. The open source Matlab function FitPsycheCurveLogit (http://matlaboratory.blogspot.in/2015/04/introduction-to-psychometric-curves-and.html) is used to fit a psychometric curve using a general linear model with a logit link function. The function uses standard MATLAB function *glmfit* to fit a binomial distribution with a logit link function. It is basically a cumulative Gaussian. The mean and variance of the Gaussian are assigned as the subject bias and subjective discrimination threshold. The function may take up to four input parameters, namely, the luminance difference between standard and comparator along X axis, perceived lightness of comparator as compared with the data along Y axis, the weights for each points and targets.

We have also fitted the data obtained from the experiment with spatial frequency varying stimuli with a modified function, developed by Wichmann and Hill (2001). They presented a cumulative Gaussian function with four parameters for fitting a psychometric function. These are mean, standard deviation, guess rate (g) and lapse rate (l). The parameters g and l constrain the limits of the cumulative distribution that provides the sigmoid shape for the psychometric curve. The plot of the same set of average psychometric data is shown in Figure 6(b). It is observed that the psychometric curves remain almost unaffected by this modification, though the family of curves appears to be more compact.

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We have also plotted in Figure 6(c), the illusory enhancement with the stimulus widths. The perceived enhancement of lightness and darkness perception decreases as the stimulus width increases. The result is qualitatively similar to that obtained in Anstis (2005).

Figure 6: Psychophysical experimental result: Average Psychometric functions for the different stimulus widths are displayed in different colors. For a particular stimulus width, the upper curve represents the condition when the comparator appears bright and the lower curve represents the condition when the comparator appears dark. While drawing the Psychometric function, a pair of curves is placed symmetrically against the luminance difference value of 0. (a) Curves are fitted using FitPsycheCurveLogit function, (b) curves are fitted using FitPsycheCurveLogit fitted function developed by Wichmann and Hill (2001), (c) Perceived enhancement of the points of subjective equality (PSE) for different stimulus widths, with respect to the physical luminance of the comparator.

Convolution results when the spatial frequency of background are varied.

An example of different stimuli and output of their convolution with DOG filter are presented in Figure 7(a) and Figure 7(b) respectively.

Figure 7: Computational simulation with a DoG filter. Four stimuli of different widths and intensity plot of their convolved values are illustrated. (a) The stimuli which are equivalent to the comparators presented in the psychophysical experiment. The black dots denote the regions of comparison during the psychophysical experiments. (b) Predicted response from a DOG filter, which has been generated by convolving the DOG filter with parameters $\sigma_c = 2, \sigma_s = 4$, $k_c = 1$ and $k_s = 1$.

Figure 8: Convolution output with a DoG filter, for different combinations of filter parameters. The marked points on the red dotted line represent the DoG filtered output, at the points of discrimination (explained by the black dots in Figure 7) for test patches lying on white bars. The blue dotted lines, on the other hand, join those points which are the filtered outputs at points of discrimination for patches lying on the black bars. In (a) Filter parameters are $k_c = 1$, $k_s = 0.8$, $\sigma_c = 0.8$, $\sigma_s = 5$, in (b) Filter parameters are $k_c = 1$, $k_s = 1$, $\sigma_c = 2$, $\sigma_s = 4$ and in (c) Filter parameters are $kc = 1$, $ks = 0.25$, $\sigma c = 0.8$, $\sigma s = 5$.

It is observed from Figure 7 and 8 that the DoG filter based simulation cannot reproduce the psychophysical experimental result presented in Figure 6(c). The present authors (Mazumdar et al., 2016) have faced similar problems while simulating the Mach band illusion with DoG filter. We have observed that any simulation with a DoG filter having fixed values of the space constants for both excitatory and inhibitory Gaussians, leads to wrong predictions as the sharpness of discontinuity in the intensity profile of the Mach band is increased. Much better simulation may be obtained if the space constant of the inhibitory Gaussian is varied with the sharpness of discontinuity. In case of step edge (i.e. at the sharpest discontinuity) no Mach band is observed, an event which may be simulated by assuming the space constant of the inhibitory

Gaussian to be zero. We, therefore, conjecture that there are situations in which the HVS prefers to filter with a single Gaussian rather than DoG. Neurophysiological data also suggest that for about 70% cells of the primary visual cortex (V1), the strength of inhibition decreases with increasing manifestations of contrast in the stimulus (Sceniak et al., 1999). It has also been reported that surround suppression of the cells in Mid Temporal (MT) area is highly contrast dependent (Tsui and Pack, 2011). It is easy to see that there are several sharp transitions in the White's stimulus, and since the sharp edge is mostly populated with high frequency components, it will not be too arbitrary to assume that such an image with large proportion of high frequency spectrum is identified and filtered by HVS with a single Gaussian inhibition or in other words simply by smoothening the picture.

We now first check whether the multiple frequency White's illusions are reproducible with a single-scale excitatory Gaussian filter. It seems unlikely and in choosing the space constant, we observe that the value of the appropriate σ_c depends on the value of the grating frequencies for realistic simulation. The filter outputs at the point of discrimination for different widths are plotted in Figure 9. It may be noted by comparing the Figure 9(a) with Figure 6(c), that simulation with small value of space constant (σ_c), yields better agreement with the psychometric curves at higher grating frequencies, but fails at lower grating frequencies. For large values of σ_c, the opposite behavior is observed, as is shown in Figure 9(b). Finally the filter output for White's illusion of different grating frequencies are generated with variable σ_c. The results are plotted in Figure 9(c). The simulation curve fitted well with the experimental psychophysical curve.

Figure 9: Variation of the Illusory enhancement (%) or, the Convolution Response (%) with the frequency of the grating are plotted. X-axis represents the grating frequency in cpd. Illusory Enhancement (in %) for experimental data or, Convolution Response (in %) for simulation data are plotted along the Y-axis. The simulated data has been normalized against the intensity value of 128. The continuous curves represent the experimental results while the dotted curves are the outcome of the computer simulation. The free parameters k_c and σ_c corresponding to the amplitude and spatial width of the Gaussian filters are varied in three different cases. k_c = 1 and σ_c = 0.8, 3.8, [0.8 1.4 2.3 3 3.8] in Figures (a), (b) and (c) respectively.

White's Illusion stimuli with varying length of the gray test patch

In the experiment with test patch of varying length/height, following 2AFC protocol, stimuli are generated following the steps given above and the subjects are asked to indicate one of the two choices (either by pressing key number one when comparator appears to have different intensity than the standard or by pressing key number two otherwise) in response to those stimuli.

Psychometric curves presented in Figure 10 are obtained by fitting the data from experiment and using the function FitPsycheCurveLogit. The illusory enhancement, with varying gray patch length and at a particular spatial frequency, are plotted in Figure 11. The perceived enhancement of lightness remains constant within the limit of the experimental error. The result is also similar to that obtained by Bakshi et. al. (2015)

Figure 10: Psychophysical experimental result: Average Psychometric functions for the different length of the gray patches are displayed in different colors. While drawing the Psychometric function, a pair of curves is placed symmetrically against the luminance difference value of 0. In (a) the length of gray patch is 8 pixels i.e. 0.738 cpd and in (b) the length of gray patch is 4 pixels i.e. 1.46 cpd

Figure 11: Perceived enhancement (%) of the points of subjective equality (PSE) for different stimulus length, with respect to the physical luminance of the comparator.

It is to be noted here that for a particular spatial frequency, the % illusory enhancement remains constant with the variation of gray patch length to the extent possible. The stimuli used for the simulation has the following parameters. The five spatial frequencies (3.67 cpd, 1.46 cpd, 0.738 cpd, 0.493 cpd and 0.368 cpd) are chosen and for each frequency the length of the gray patch is varied in the range of 70 pixels to 2 pixels in descending order with intermediate values as 60 pixels, 50 pixels, 40 pixels, 32 pixels, 24 pixels, 16 pixels, 14 pixels, 12 pixels, 10 pixels, 8 pixels, 6 pixels, 4 pixels and 2 pixels.

The stimuli are now filtered with the proposed Gaussian kernels of varying σ_c. The value of the spatial frequencies, corresponding length of the gray patch and the scale factor of the Gaussian kernels are presented in Table-2. It is to be noted here that to keep the appropriate variation of the Gaussian kernel, the mask size is chosen approximately 3 times the corresponding spatial width. As it is obtained in the psychometric experiment, the illusory enhancement measured in (%), remain constant with the variation of the length of the gray patch. The same is reflected in the simulation result as depicted in Figure 12. A point to be emphasized at this juncture that the scale factor of the Gaussian kernel remains constant till the width of the bars and the length of the gray patch are widely different. As soon as they become comparable the scale factor changes significantly as shown in Table 2. The convolution output at different spatial frequency, different patch length is plotted in Figure 12.

Table 2: Parameters of the stimuli and the filter used in the simulation with varying spatial frequencies and the length of the gray patch

Figure 12: Filter response (%) for different length of the gray patch at a particular spatial frequency. In the graph, the red, blue, green, cyan and magenta curves show the simulated output at 3.67cpd, 1.46 cpd, 0.738 cpd, 0.493 cpd and 0.368 cpd respectively.

Figure 13: Experimental data on illusory enhancement (%) as a function of grating frequency plotted in the logarithmic scale. The logarithm of % illusory enhancement data has been taken

before normalization within 0 and 2.

Experimental data on % illusory enhancement as a function of grating frequency is plotted in Figure 13, in logarithmic scale. This experimental data belongs to the gray patch length of 70 pixels. The linear nature of the variation bears close similarity with the graph shown in Figure 1.1(b) of Anstis (2005). The experimental data on % illusory enhancement as a function of gray patch length is next plotted in Figure 14. Finally, the variation of the scale factor of the Gaussian filter with the grating frequency has been plotted in Figure 15. Each graph shows the variation for a particular gray patch length.

Figure 14: Experimental data on illusory enhancement (%) as a function of patch length in pixels plotted. The % illusory enhancement data has been taken after normalization within 0 and 2.

Figure15: Variation of the scale factor of the Gaussian filter with the grating frequency has been plotted. The nature of the graph shows close resemblance at different gray patch length.

Discussion

It is well known that the simultaneous brightness contrast (SBC) and the White's illusion (WI) show strikingly contrastive behavior so far as lateral inhibition phenomena is concerned. Psychometric data on SBC (Shi et al., 2013), can be explained using a DoG based linear filter model. However, WI cannot be explained by invoking the principle of lateral inhibition. It is also generally believed that the White's effect is not a manifestation of the brightness assimilation phenomenon. However, in this work we have attempted to model the White's effect from the perspective of assimilation. We propose a linear filter in which the lateral inhibition part of the centre-surround model is suppressed for all practical purposes. Previously we had used an adaptive DOG filter (Mazumdar et. al., 2016) to model the variation of the spatial characteristics of the centre-surround receptive field to explain the variation of the width of Mach bands with the sharpness of discontinuity in the intensity profile of an edge. A Fourier analysis based adaptive model proposed in that work showed that the effect of surround suppression had to be reduced as the contrast at the edge increased. In the extreme limit of binary edges, where the contrast is maximum and represented by a step edge, no lateral inhibition takes place, so that over there the DoG kernel gets converted into a Gaussian kernel without any surround, the reason that the Mach band vanishes at a perfect step transition. It should be noted here that the spectrum of step edges are very rich with high frequency components. Extending the argument in case of White's illusion, where there are several strong edges, the reason why the spectrum is rich in high frequency components, we propose a Gaussian kernel to explain the visual process in the framework of a linear filter method.

Early literature in psychophysics and visual neuroscience also bears substantial evidence regarding the importance of the phenomenon of brightness assimilation (Helson 1963; Beck 1966) Especially important are the works of Reid and Shapley (1988) and de Weert who have hypothesized from their experimental findings the existence of large integrating receptive fields in the visual cortex devoid of center-surround antagonism. Another very important evidence, that sets up a possible link of lightness assimilation with White's effect type of stimulus, comes from an old work of Arend et al. (1971) who pointed out that for complex visual stimuli, contrast borders which are too far off to modulate local retinal mechanisms, may, affect the brightness sensation through long distance integrations. Although the Oriented Difference of Gaussians (ODOG) filter of Blakeslee and McCourt (1999, 2004) have made a similar attempt achieving success to quite an extent, Bakshi & Ghosh (2012) and Bakshi et al. (2015) have already shown the limitations of this model of lightness perception in explaining illusory effects at high frequency edges and beyond certain scales. Moreover, there is no known neural correlate of the contrast normalization step in Blakeslee and McCourt's algorithm. In contrast, multi-scale filtering and integration over small to large scales, as we have already seen, is a well-accepted fact for neuroscientists and psychologists alike. Multi-scale integration (Rudd & Zemach 2004, 2005) is a hot domain of research not only in biological information processing, but also among the computer vision community. The present work may provide some clues in that direction too.

Conclusions

In this work we have studied the properties of the White's illusion by varying both the spatial frequency of the background grating and the length or height of the gray test patches under consideration. We propose that for both such variations the perception of the White's illusion can be understood through the phenomenon of lightness assimilation and by modeling the same through Gaussian kernels at different scales. The Gaussian filter model is used to fit the psychometric test data with the simulation. Wide variation in spatial frequency and length of the gray patch is used to prove the appropriateness of the model especially in the light of the fact that neither the isotropic DoG, nor the well-established ODOG model can successfully explain such a wide variation of test patch height in White's illusion. While the Gaussian filter is clearly advantageous over the classical DoG as also the ODOG for elongated test patches, it is also found to be surprisingly effective even for the smaller patches with reverse aspect ratio through considering larger space constants or scales, physically meaning integration over wider areas. Both the assumptions of the proposed model, viz. suppression of inhibitory surround and hence spatial filtering by Gaussian only, and the possible integration of intensity information over comparatively larger receptive fields, have the backing of several neurophysiological evidences in literature.

Additional Information and Declarations

Competing Interests
The authors do not have any competing interest

Author Contributions
Soma Mitra conceived and designed the experiments, performed the experiments, analyzed the data, wrote the paper, ran computational simulations.
Debasis Mazumdar performed the experiments.
Debasis Mazumdar, Kuntal Ghosh and KamalesBhaumik conceived and designed the

experiments, analyzed the data, wrote the paper.

Ethics

The authors have followed the COPE guidelines for ethical responsibilities and written consent was obtained from all subjects.

Funding

This study was funded by MeitY and MOSPI (through TAC-DCSW, CCSD, ISI), Govt. of India. The funding agencies had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Acknowledgement

The first two authors are thankful to the MeitY, Govt. of India for sponsoring the project titled 'Development of Human perception inspired algorithms for solving deeper problem in Image Processing and Computer vision ', Administrative approval No: DIT/R&D/C-DAC/2(7)/2010 dated March 28, 2011. The authors would also like to thank Ms. Gargi Bag, CDAC, Kolkata for helping in the development of the MATLAB code.

References

Anstis SM. 2005. White's effect in color, luminance and motion. In: *Harris L & Jenkin M (Eds): Seeing Spatial Form*, Oxford University Press.

Arend L.E, Buehler, J.N, Lockhead, G.R. 1971. Difference Information in Brightness Perception. *Perception and Psychophysics.***9**: 367-370.

Bakshi A, Ghosh K. 2012. Some insights into why the perception of Mach bands is strong for luminance ramps and weak or vanishing for luminance steps. *Perception* 41: 1403–1408

Bakshi A, Roy S, Mallick A, Ghosh K. 2015. Limitations of the Oriented Difference of Gaussian Filter in Special Cases of Brightness Perception Illusions. *Perception* 45: 328-36

Beck J. 1966. Contrast and Assimilation in Lightness Judgments. *Perception and Psychophysics* 1: 342-344

Blakeslee B, McCourt ME. 1999. A multiscale spatial filtering account of the White effect, simultaneous brightness contrast and grating induction. *Vision Res* 39: 4361 – 4377

Blakeslee B, McCourt ME. 2004. A unified theory of brightness contrast and assimilation incorporating oriented multiscale spatial filtering and contrast normalization. *Vision Res* 44: 2483 – 2503

Blakeslee B, Padmanabhan G, McCourt ME. 2016. Dissecting the influence of the Collinear and Flanking Bars in White's Effect. *Vision Research* **127**: 11-17

de Weert CMM. 1991. Assimilation versus Contrast. In: Valberg A., Lee B.B. (eds) From Pigments to Perception. NATO ASI Series (Series A: Life Sciences), vol **203**. Springer, Boston, MA

de Weert CMM, Spillmann L. 1995. Assimilation: Asymmetry Between Brightness and Darkness. *Vision Research* **35**:1413-1419

Fechner, Gustav Theodor.1889. Elemente der Psychophysik (2 Volumes) *(2nd ed.). Leipzig: Breitkopf & Härtel.* Vol **2**

Gindy SS. 1963. Techniques for subjective colour measurement and their application to colour contrast phenomena *PhD Thesis,* London University, UK

Helson H. 1963. Studies of Anomalous Contrast and Assimilation. *Journal of the Optical Society of America.* 53: 179-184

Hubel DH, Wiesel TN. 1962. Receptive Fields, Binocular Interaction and Functional Architecture in The Cat's Visual Cortex. *J Physiol* **60**: 106–154

Kingdom F, Moulden B. 1991. White's effect and assimilation. *Vision Res* **31**: 151-159

Kuffler SW. 1953. Discharge patterns and functional organization of mammalian retina. *J Neurophysiol* **16**: 37-68

Macknik SL, Martinez-Conde S, Haglund MM. 2000. The role of spatiotemporal edges in visibility and visual masking. *Proceedings of the National Academy of Sciences of the United States of America* **97**:7556–7560

Marr D. 1982. Vision: A Computational Investigation into the Human Representation and Processing of Visual Information. *WH Freeman*, New York

Mazumdar D, Mitra S, Ghosh K, Bhaumik K. 2016. A DOG filter model of the occurrence of Mach bands on spatial contrast discontinuities. *Biological Cybernetics* **110**: 229-236

Munker H. 1970. Farbigegitter, abbildung auf der netzhaut und übertragungstheoretischebeschreibungderfarbwahrnehmung [Coloured grids, picture on the net skin and transference-theoretical description of the colour perception] *Postdoctoral Qualification Report*, Ludwig-Maximilians-Universität, Germany.

Reid RC, Shapley R. 1988. Brightness Induction by Local Contrast, and the Spatial Dependence of Assimilation. *Vision Research* **28**:115-132.

Rodieck RW, Stone J. 1965. Analysis of receptive fields of cat retinal ganglion cells. *J Neurophysiol* **28**: 833–849

Rudd ME, Zemach IK. 2004. Quantitative properties of achromatic color induction: An edge integration analysis. *Vision Research* **44**: 971–981

Rudd ME, Zemach IK. 2005. The highest luminance rule in achromatic color perception: Some counter examples and an alternative theory. *Journal of Vision* **5**: 983–1003

Sceniak MP, Ringach DL, Hawken MJ, Shapley R. 1999 "Contrast's effect on spatial summation by macaque V1 neurons" Nature Neuroscience 2: 733-739

Shi V, Cui J, Troncoso XG, Macknik SL, Martinez-Conde S. 2013. Effect of stimulus width on simultaneous contrast. *PeerJ* **1**:e146 DOI 10.7717/peerj.146

Troncoso XG, Macknik SL, Martinez-Conde S. 2005. Novel visual illusions related to Vasarely's "nested squares" show that corner salience varies with corner angle. *Perception* **34**:409–420

Troncoso XG, Tse PU, Macknik SL, Caplovitz GP, Hsieh P-J, Schlegel AA, Otero-Millan J, Martinez-Conde S. 2007. BOLD activation varies parametrically with corner angle throughout human retinotopic cortex, *Perception* **36**:808–820 DOI 10.1068/p5610

Troncoso X G, Macknik SL, Martinez-Conde S. 2009. Corner salience varies linearly with corner angle during flicker-augmented contrast: a general principle of corner perception based on Vasarely's artworks', *Spatial Vision* **22**:211–224 DOI 10.1163/156856809788313129

Tsui JM, Pack CC. 2011. Contrast sensitivity of MT receptive field centers and surrounds. *J Neurophysiol* **106**: 1888-1900

White M. 1979. A new effect of pattern on perceived lightness. *Perception* **8**:413–416

White M. 2010. The early history of White's illusion. *Color: Design & Creativity* **7**:1-7

White M. 1981. The effect of the nature of the surround on the perceived lightness of gray bars within square wave test gratings. *Perception* **10**:215-230

Wichmann FA, Hill NJ. 2001. The psychometric function: I. Fitting, sampling, and goodness of fit. *Perception & Psychophysics* **63**:1293-1313

Figure 1

The White’s illusion

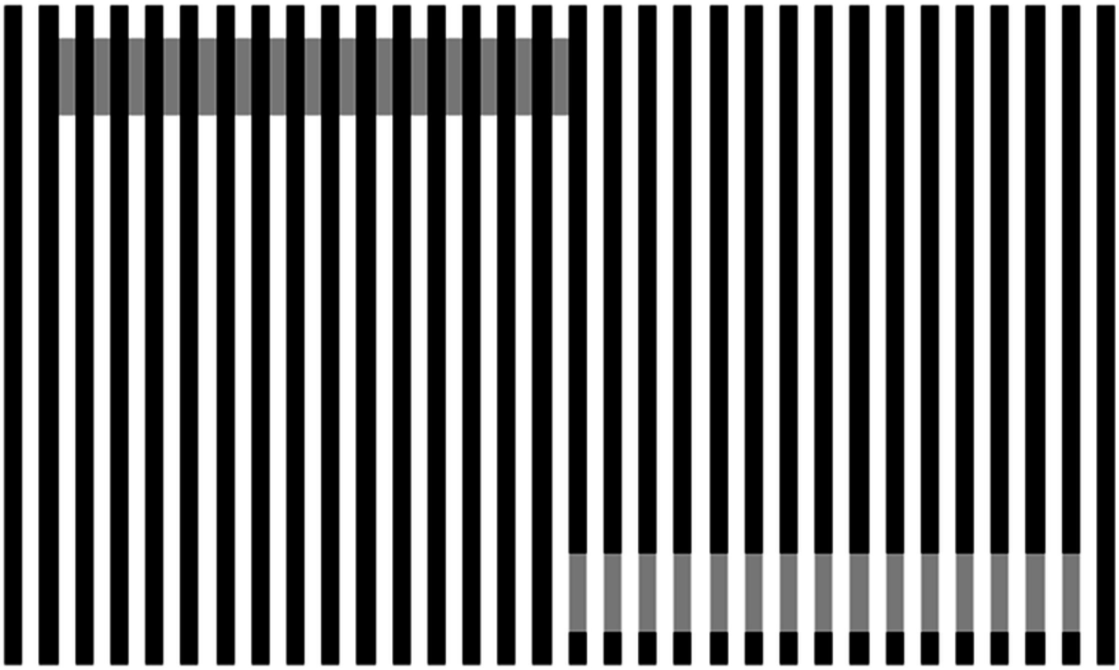

Figure 2

The pincushion stimulus adopted from de Waart and Spillmann (1995)

**Note: Auto Gamma Correction was used for the image. This only affects the reviewing manuscript. See original source image if needed for review.*

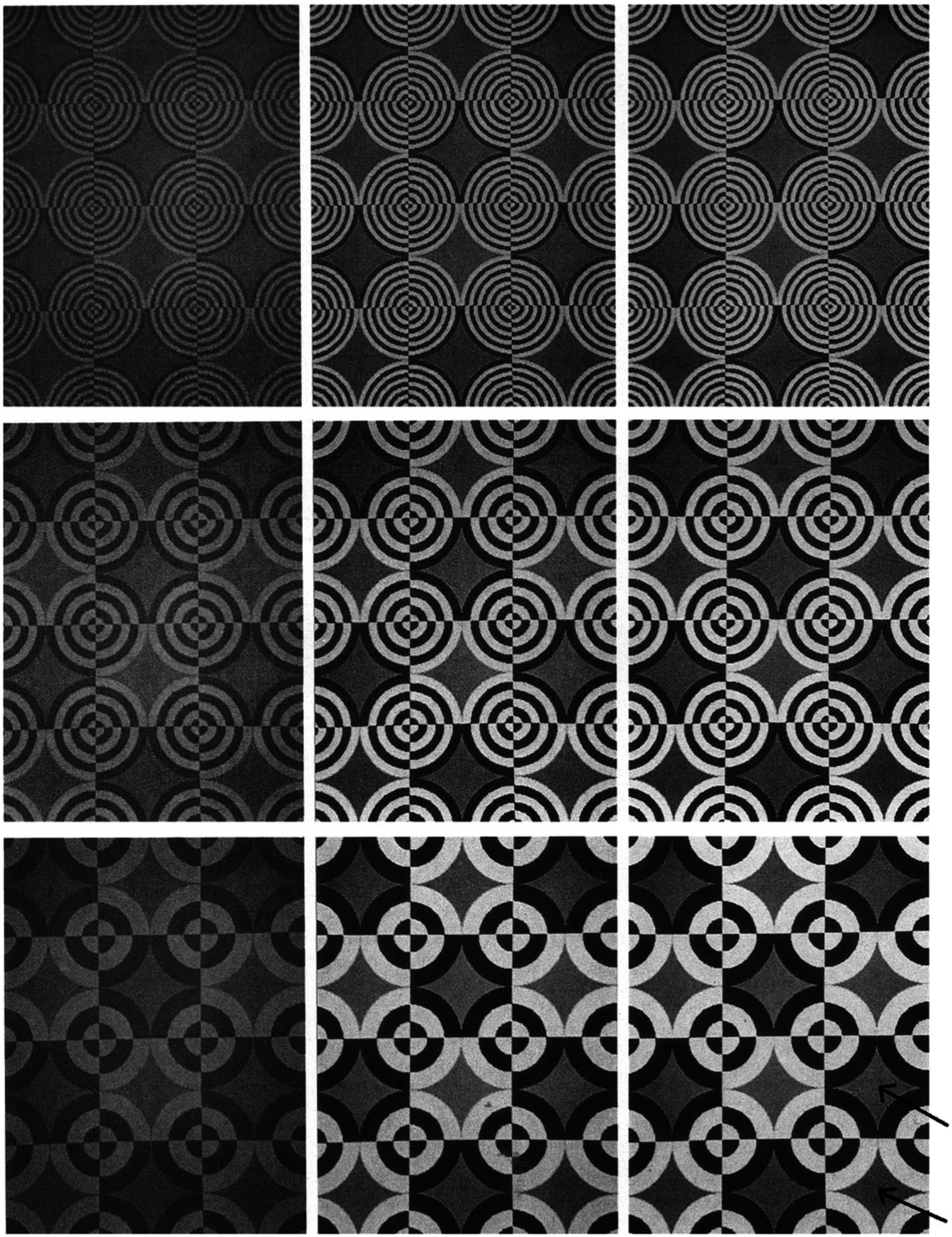

Figure 3

White's illusion at 5 different grating widths

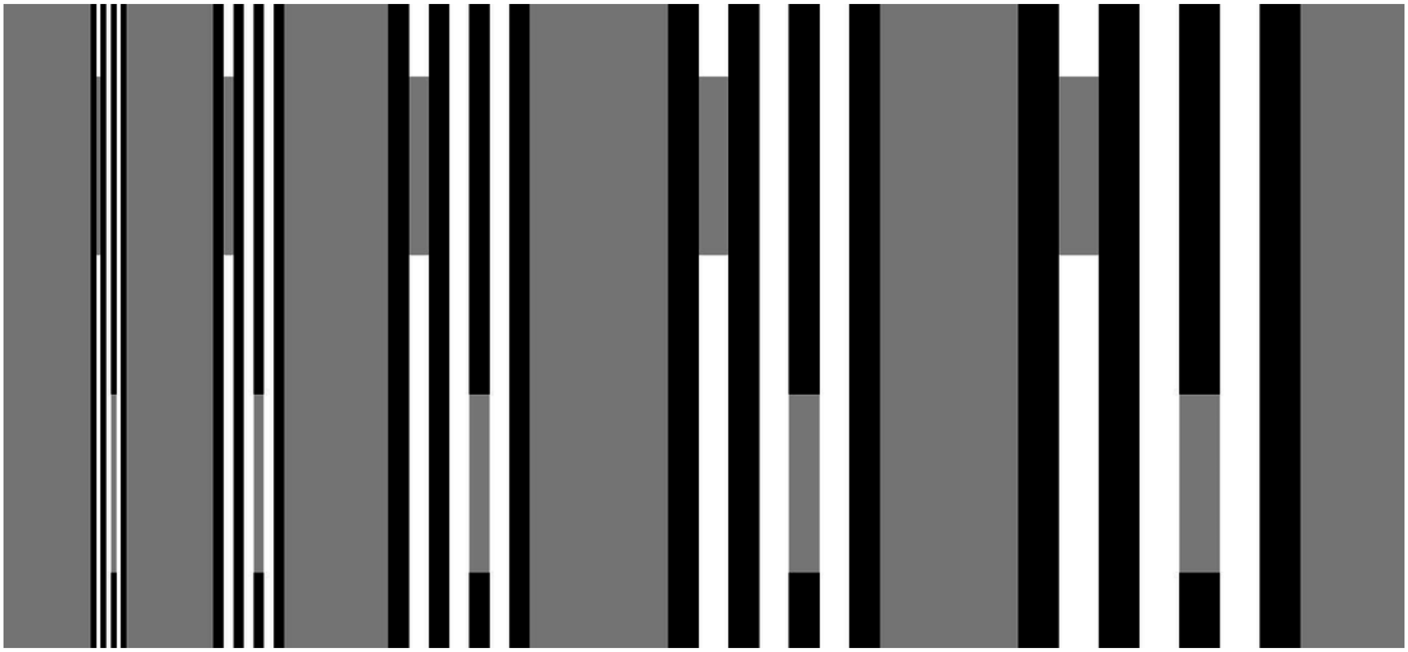

Figure 4

White’s illusion at 10 different gray patch lengths

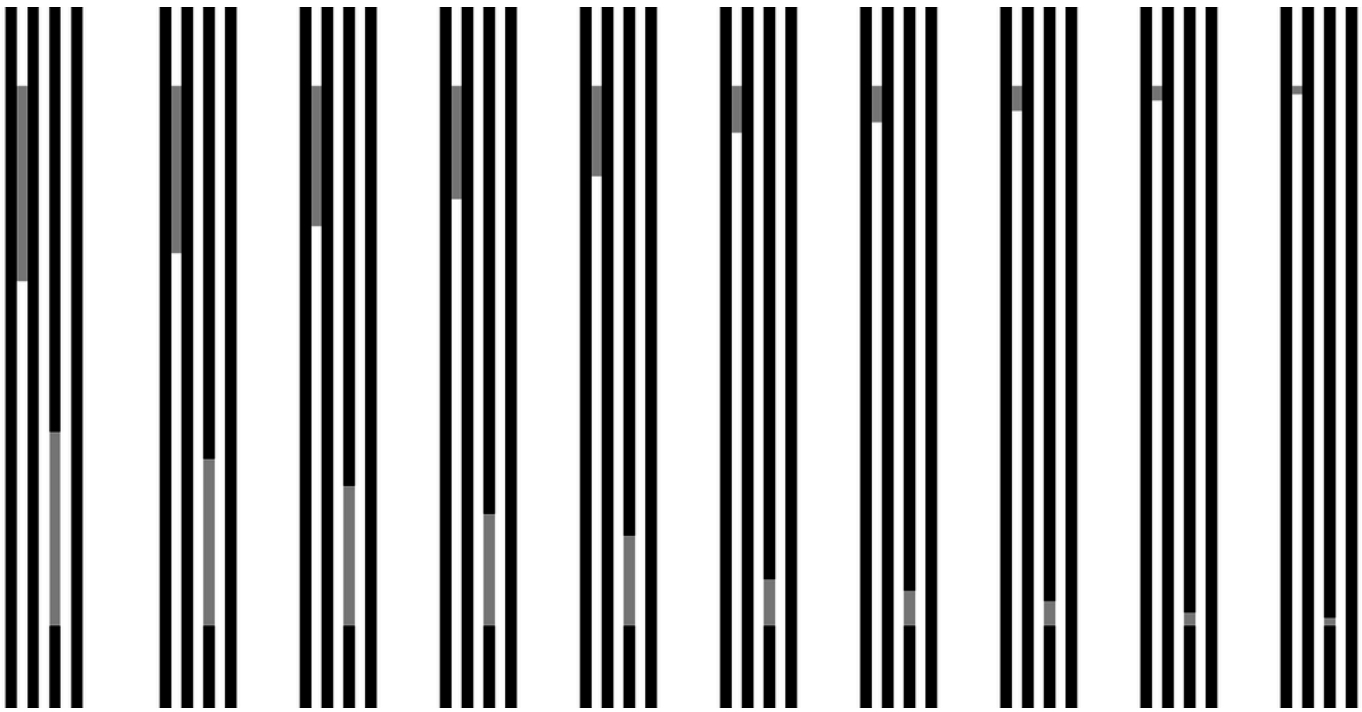

Figure 5

The psychophysical experiment set-up for lightness discrimination in White's illusion

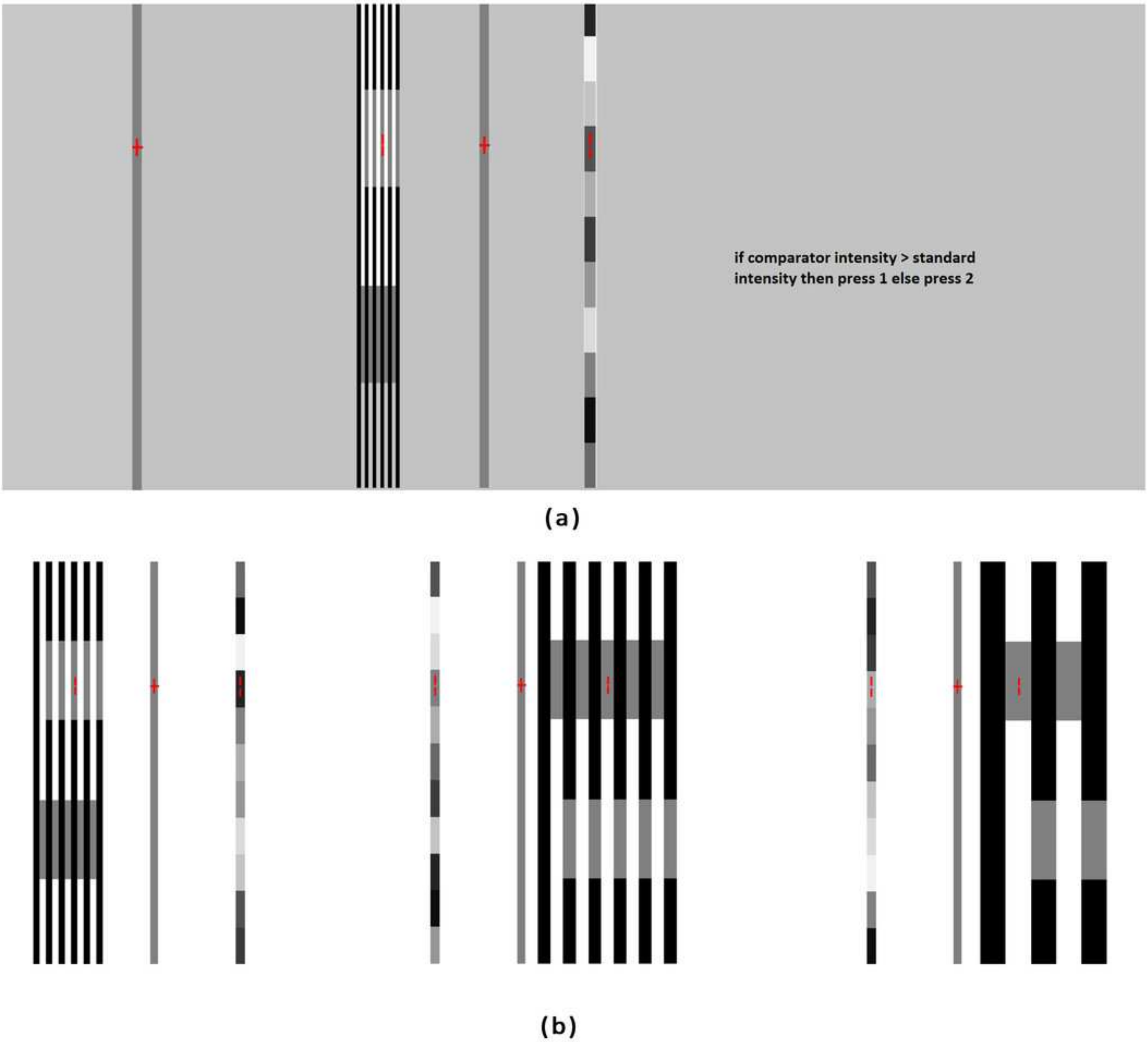

Table 1(on next page)

Specification of the parameters of the test pattern used in psychometric test

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Sl No	Stimulus feature	Number of variations	Parameter values/location
1.	Comparator width	5	3.67 cpd, 1.46 cpd, 0.738 cpd, 0.493 cpd and 0.368 cpd
2.	inducing gradient luminance at the point of comparison	2	Gray 50% (128) bar with the coaxial black region. Gray 50% (128) bar with the coaxial white region.
3.	Standard luminance	11	5%, 14%, 23%, 32%, 41%, 50%, 59%, 68%, 77%, 86% and 95% (11,13, 36, 59, 82, 105, 128, 150, 173, 196, 219, 242)
4.	Screen positions	2	Left Right
5.	Fixation cross location	2	Top Bottom

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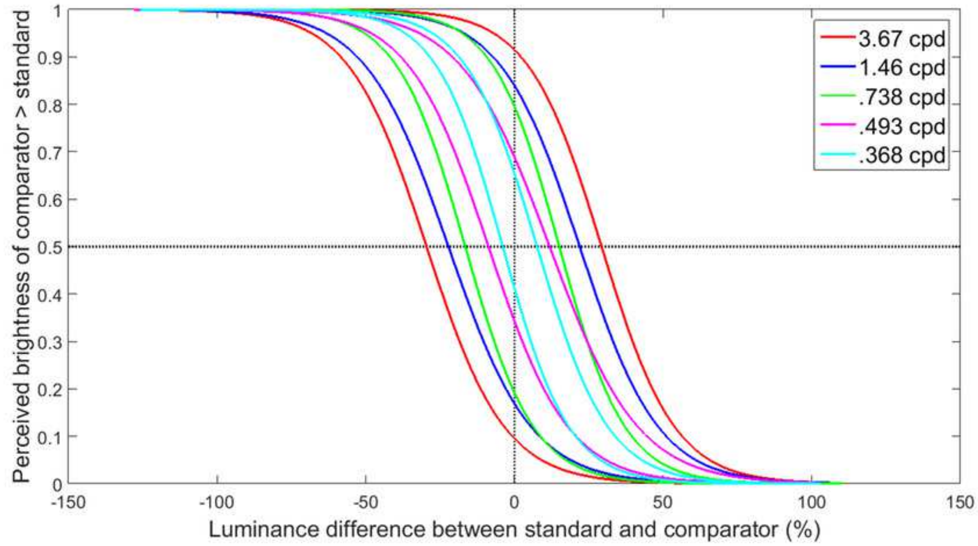
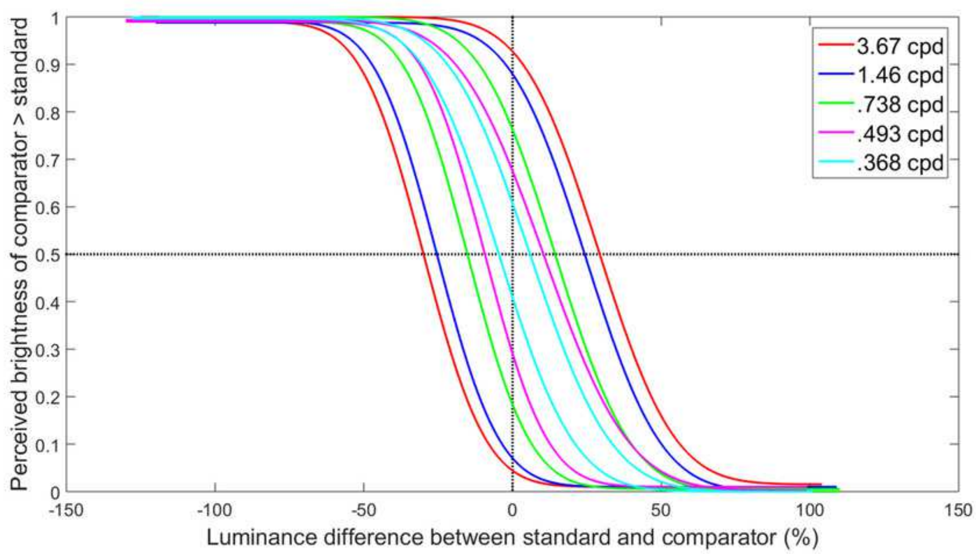
Figure 6

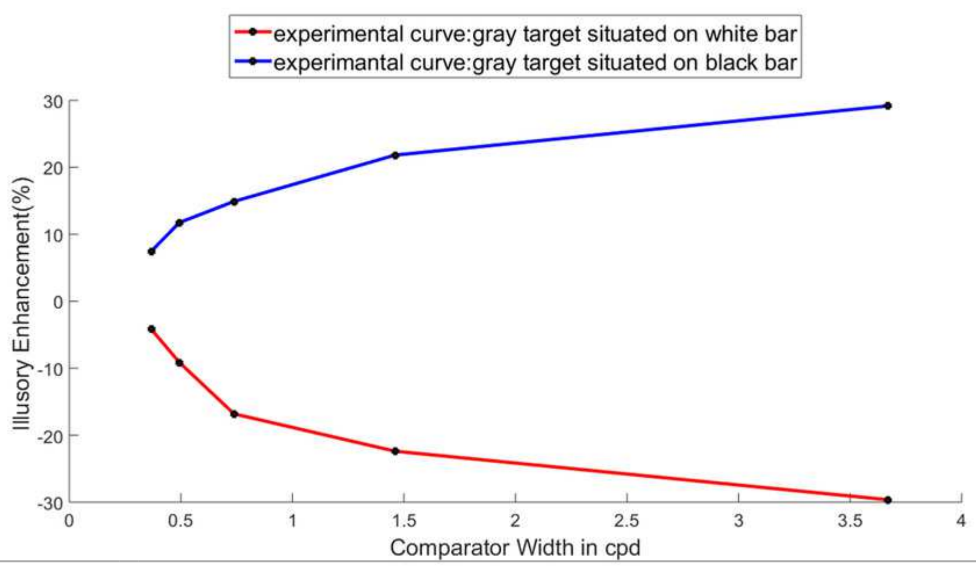
Results of the psychophysical experiment


Perceived brightness of comparator > standard
Luminance difference between standard and comparator (%)
3.67 cpd
1.46 cpd
.738 cpd
.493 cpd
.368 cpd

(a)


Perceived brightness of comparator > standard
Luminance difference between standard and comparator (%)
3.67 cpd
1.46 cpd
.738 cpd
.493 cpd
.368 cpd

(b)


experimental curve:gray target situated on white bar
experimantal curve:gray target situated on black bar
Illusory Enhancement(%)
Comparator Width in cpd

(c)

Figure 7

Computational simulation with DoG filter on White's stimuli of four different widths

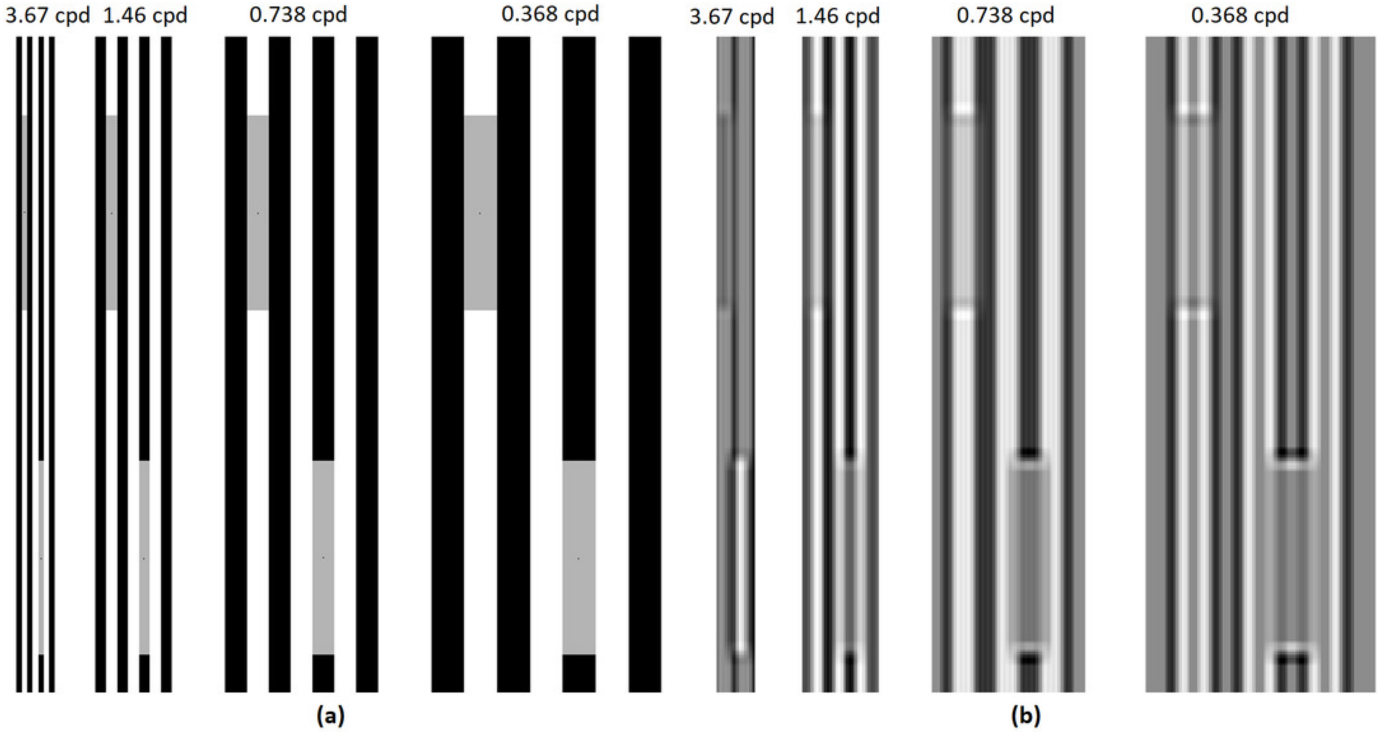


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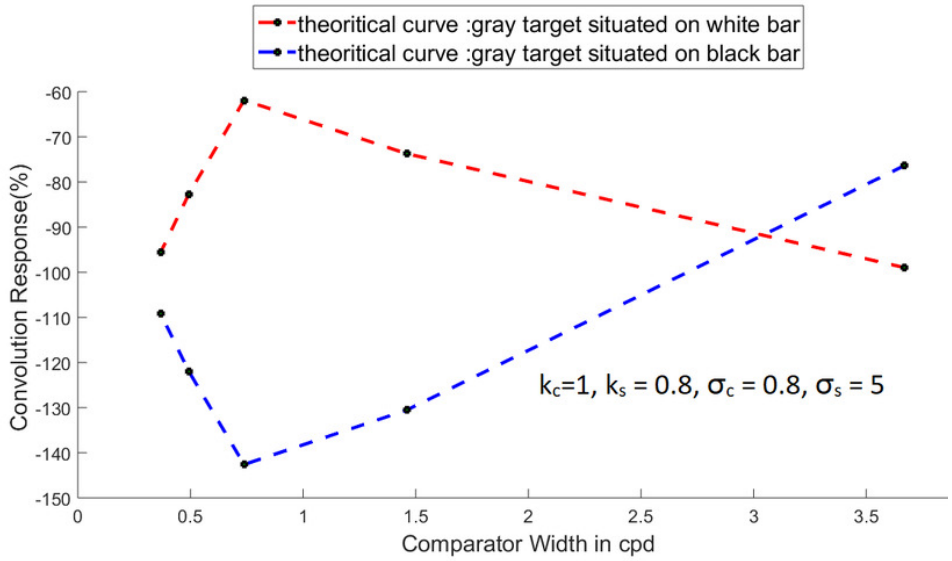
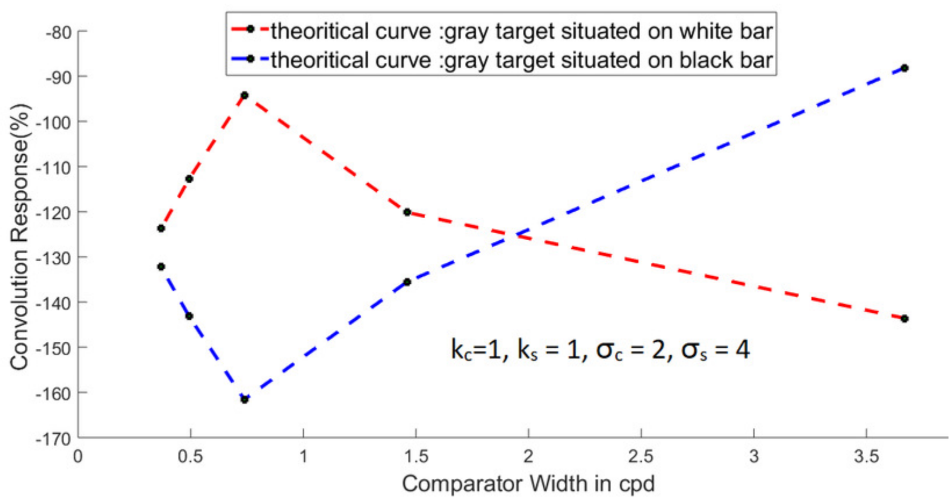
Figure 8

Convolution output with a DoG filter, for different combinations of filter parameters



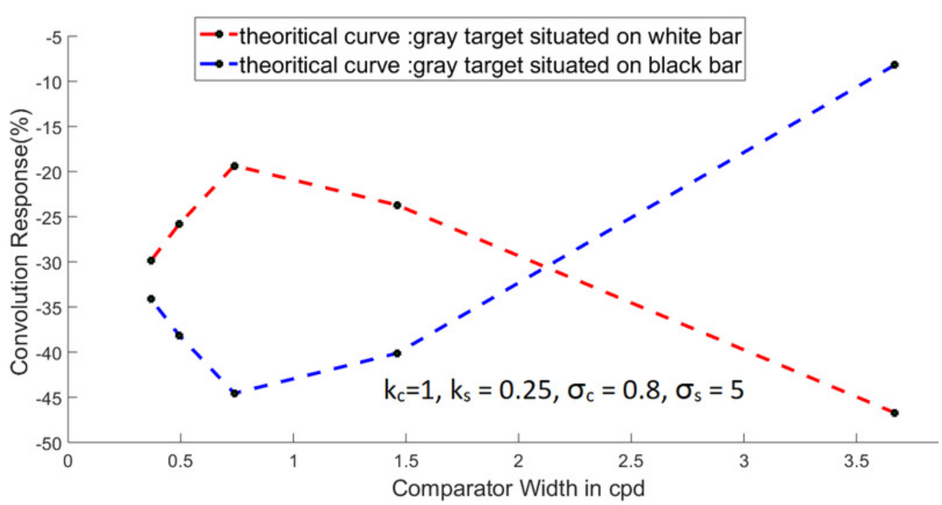
theoritical curve :gray target situated on white bar
theoritical curve :gray target situated on black bar
Convolution Response(%)
Comparator Width in cpd
kc=1, ks = 0.8, σc = 0.8, σs = 5

(a)



theoritical curve :gray target situated on white bar
theoritical curve :gray target situated on black bar
Convolution Response(%)
Comparator Width in cpd
kc=1, ks = 1, σc = 2, σs = 4

(b)

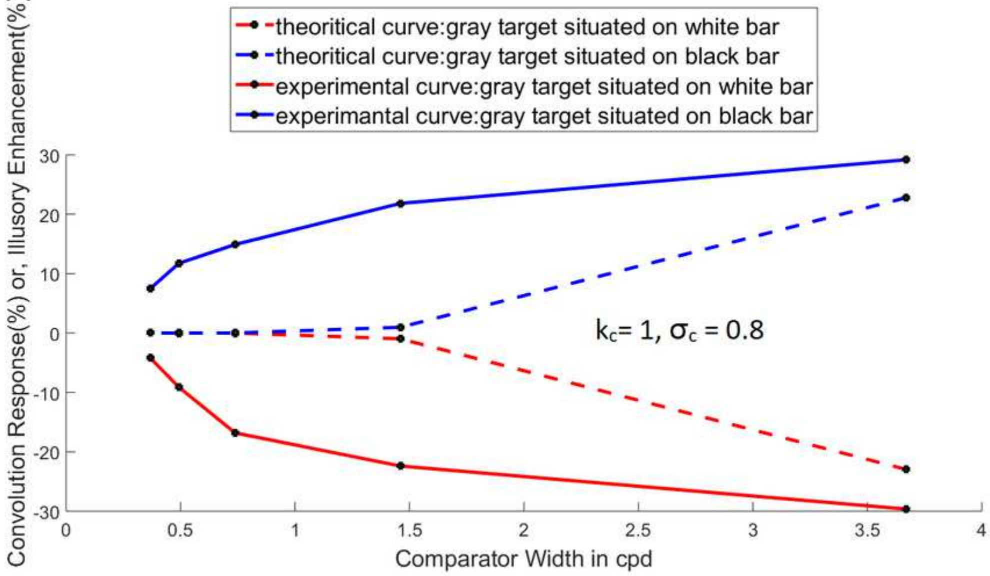


theoritical curve :gray target situated on white bar
theoritical curve :gray target situated on black bar
Convolution Response(%)
Comparator Width in cpd
kc=1, ks = 0.25, σc = 0.8, σs = 5

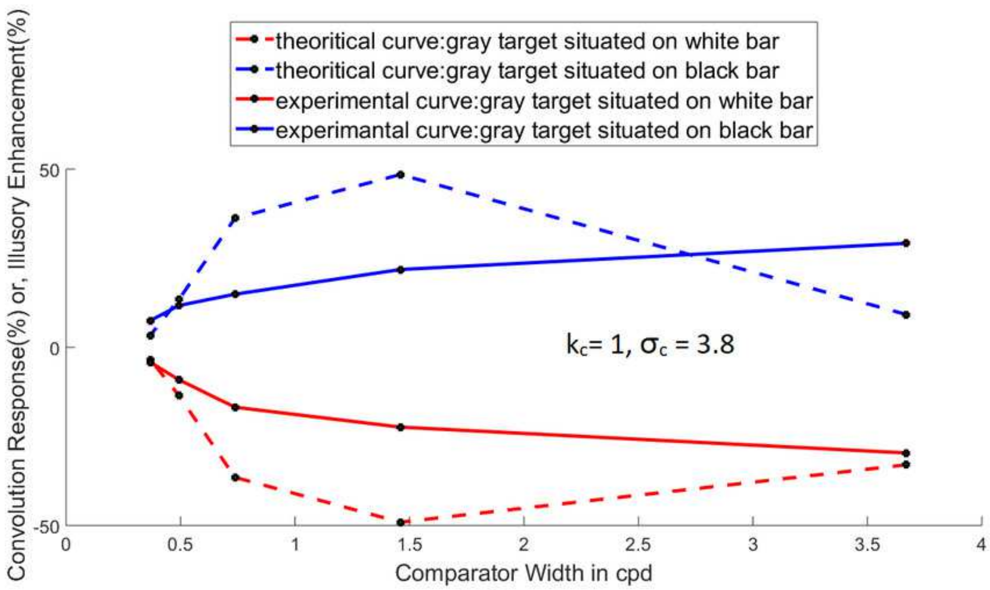
(c)

Figure 9

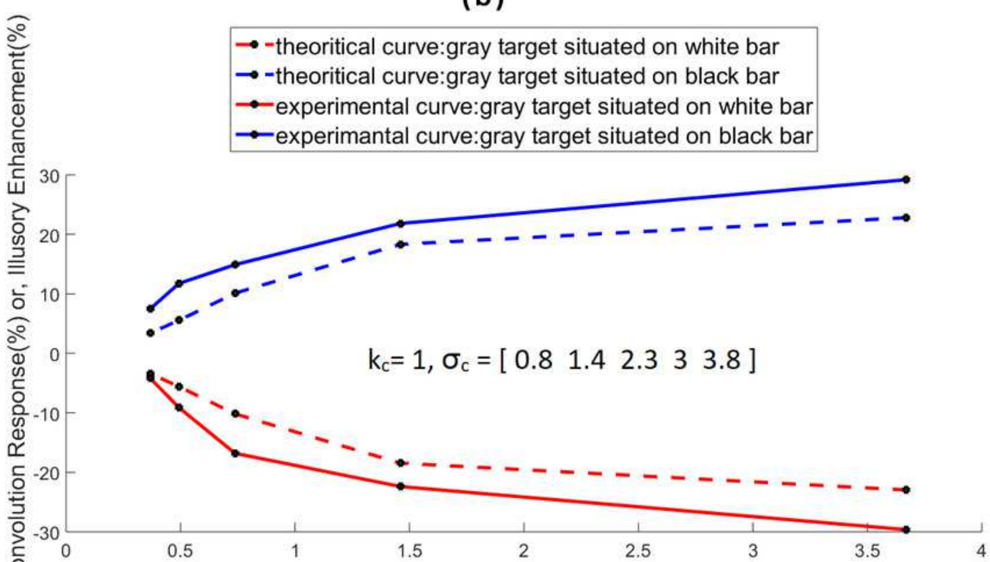
Variation of the illusory enhancement (%) and simulted response (%) with the frequency of the grating


theoritical curve:gray target situated on white bar
theoritical curve:gray target situated on black bar
experimental curve:gray target situated on white bar
experimantal curve:gray target situated on black bar
k_c= 1, σ_c = 0.8
Convolution Response(%) or, Illusory Enhancement(%)
Comparator Width in cpd

(a)


theoritical curve:gray target situated on white bar
theoritical curve:gray target situated on black bar
experimental curve:gray target situated on white bar
experimantal curve:gray target situated on black bar
k_c= 1, σ_c = 3.8
Convolution Response(%) or, Illusory Enhancement(%)
Comparator Width in cpd

(b)


theoritical curve:gray target situated on white bar
theoritical curve:gray target situated on black bar
experimental curve:gray target situated on white bar
experimantal curve:gray target situated on black bar
k_c= 1, σ_c = [0.8 1.4 2.3 3 3.8]
Convolution Response(%) or, Illusory Enhancement(%)
Comparator Width in cpd

(c)

Figure 10

Average Psychometric functions for different lengths of gray patches

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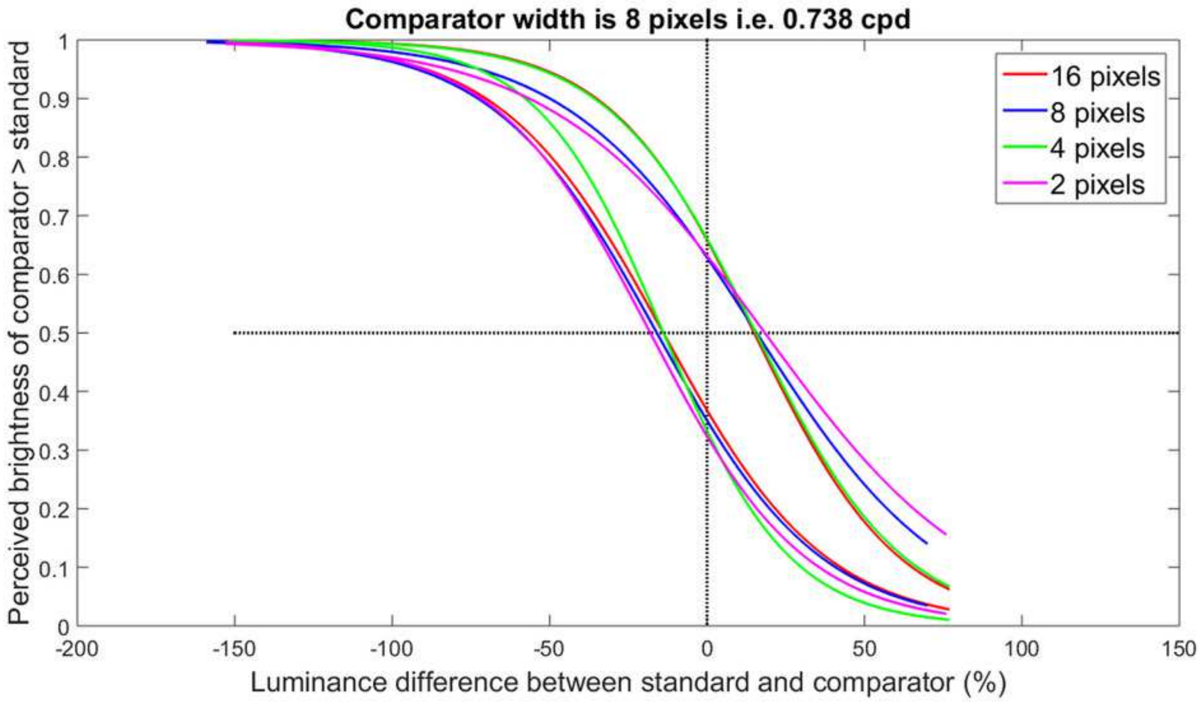
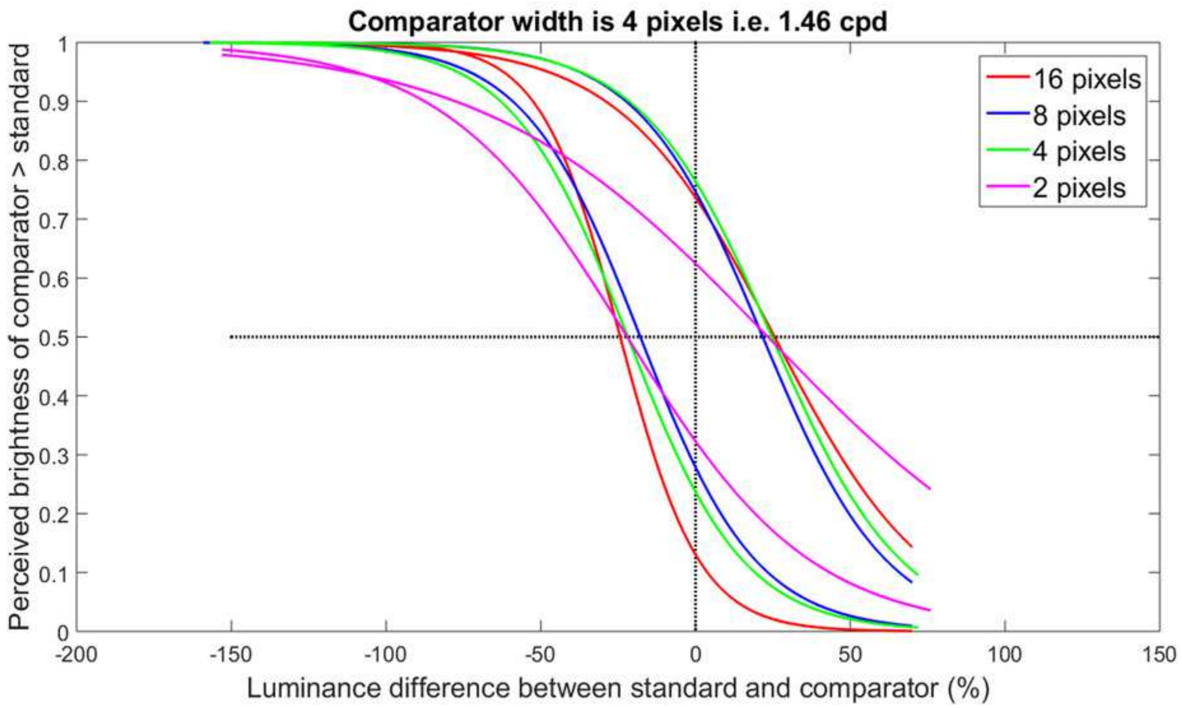

Comparator width is 8 pixels i.e. 0.738 cpd
16 pixels
8 pixels
4 pixels
2 pixels
Perceived brightness of comparator > standard
Luminance difference between standard and comparator (%)

(a)


Comparator width is 4 pixels i.e. 1.46 cpd
16 pixels
8 pixels
4 pixels
2 pixels
Perceived brightness of comparator > standard
Luminance difference between standard and comparator (%)

(b)

Figure 11

Perceived enhancement (%) of the points of subjective equality (PSE) for different stimuli lengths

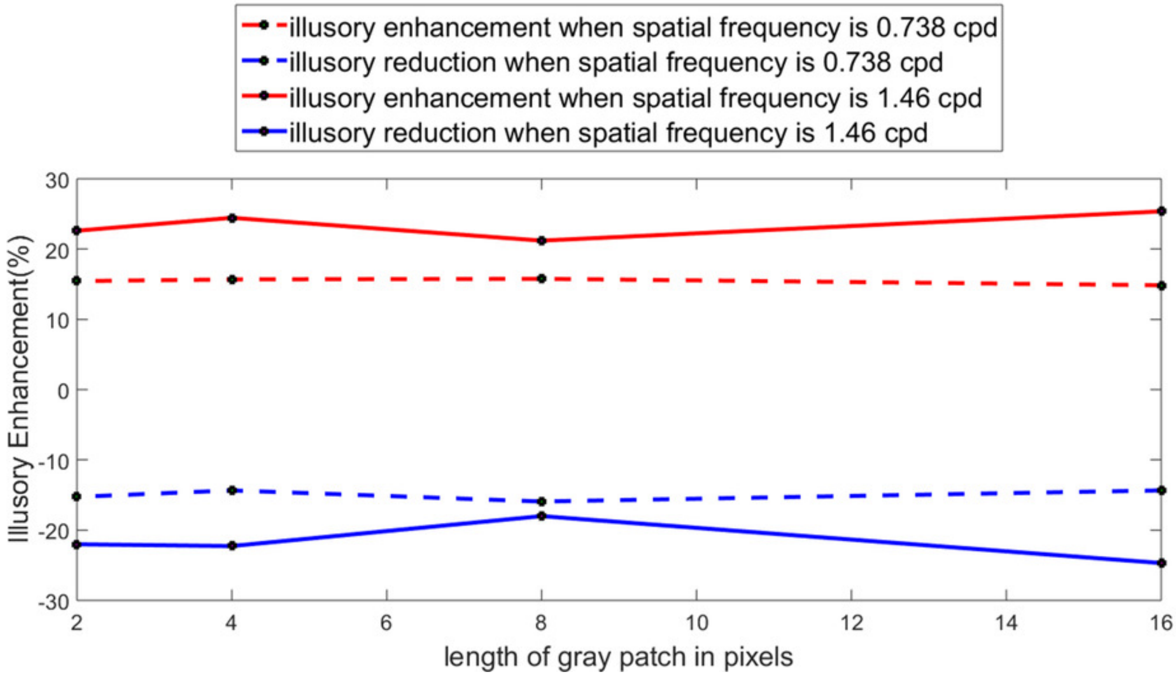


Table 2 (on next page)

Parameters of the stimuli and the filter used in the simulation with varying spatial frequencies and the length of the gray patch

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Length of gray patch in pixels	Scale factor				
	Spatial frequency =3.67 cpd(2 pix) Mask size =(6 x6)	Spatial frequency =1.46 cpd(4 pix) Mask size =(12 x 12)	Spatial frequency =0.738 cpd(8 pix) Mask size =(20 x 20)	Spatial frequency =0.493 cpd(12 pix) Mask size =(35 x 35)	Spatial frequency =0.368 cpd(16 pix) Mask size =(50 x 50)
70	0.8	1.4	2.3	3	3.6
60	0.8	1.4	2.3	3	3.6
50	0.8	1.4	2.3	3	3.6
40	0.8	1.4	2.3	3	3.6
32	0.8	1.4	2.3	3	3.6
24	0.8	1.4	2.3	3	3.6
16	0.8	1.4	2.3	3.1	5.7
14	0.8	1.4	2.3	3.6	7.3
12	0.8	1.4	2.4	4.9	8.5
10	0.8	1.4	2.7	6.15	9.5
8	0.8	1.41	3.8	7.2	10.4
6	0.8	1.53	5.1	8.1	11.3
4	0.81	2.35	6.35	9	12.1
2	1.32	3.32	7.8	9.8	12.9

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Figure 12

Filter response (%) for different lengths of the gray patch at a particular spatial frequency.

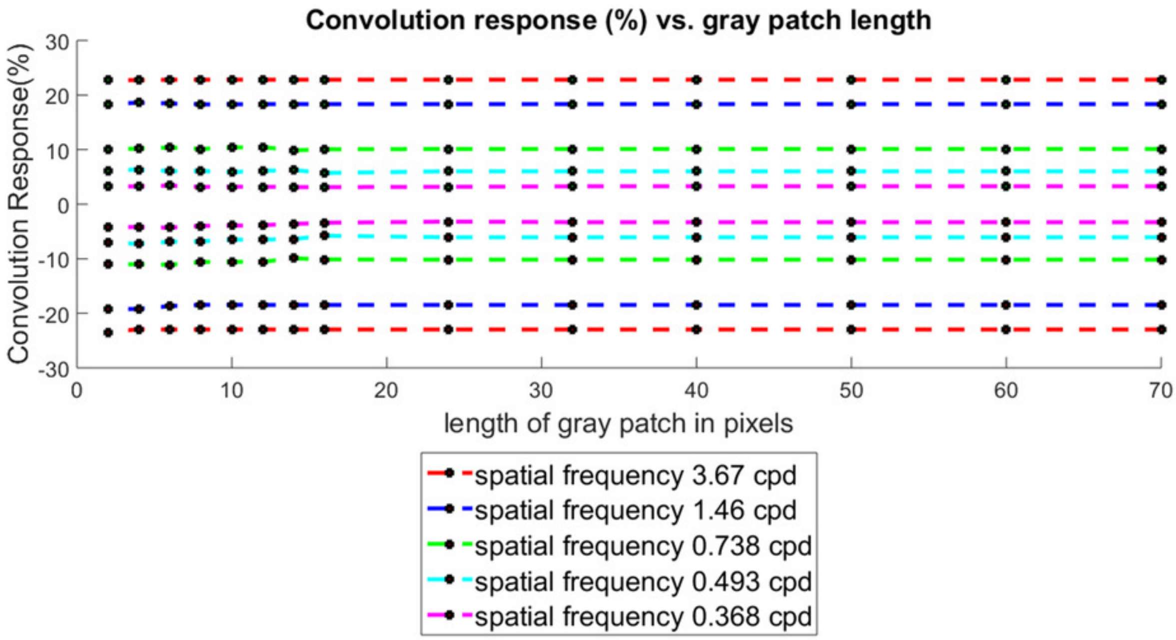

Figure 13

Experimental data on illusory enhancement (%) as a function of grating frequency

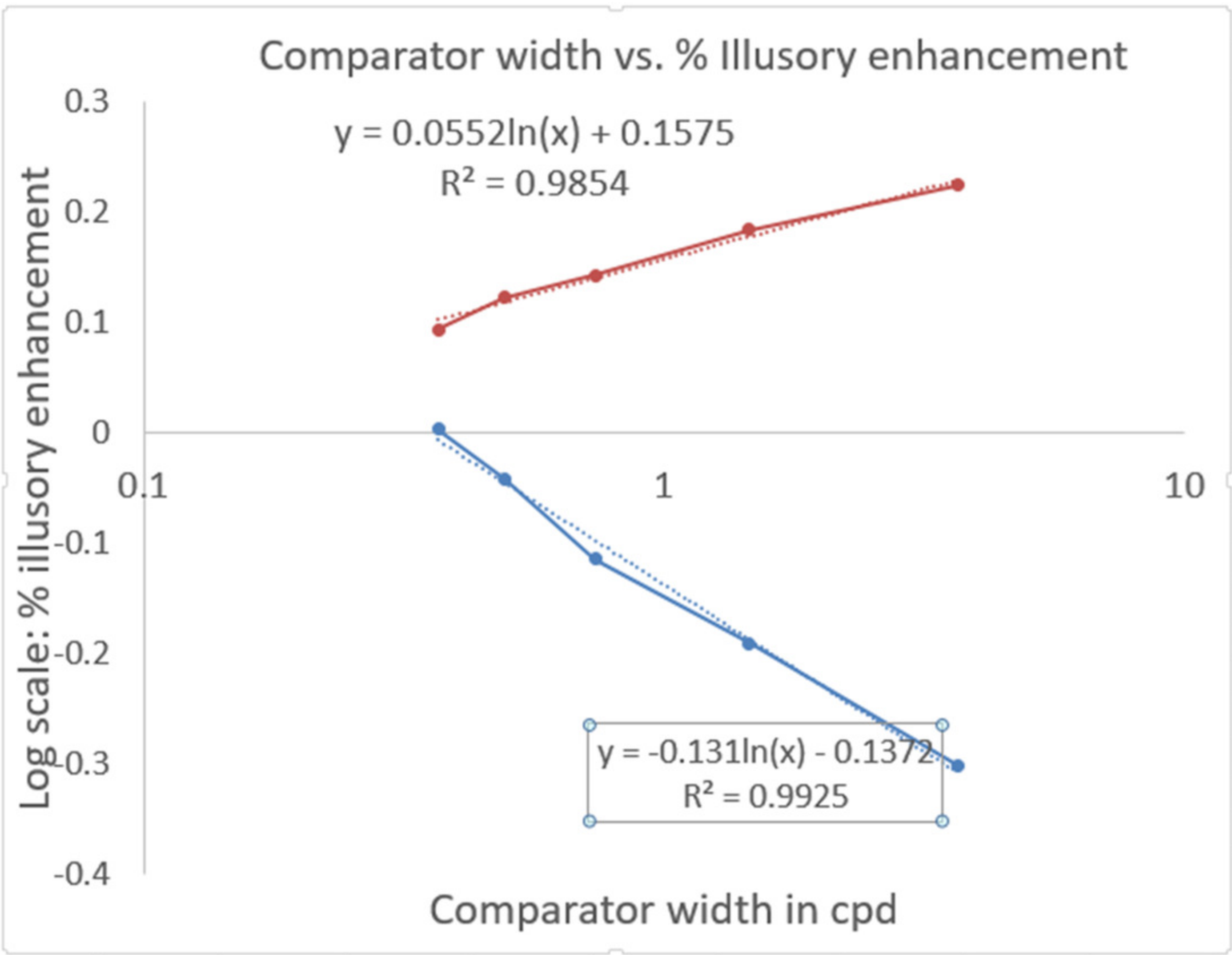

Figure 14

Experimental data on illusory enhancement (%) as a function of patch length

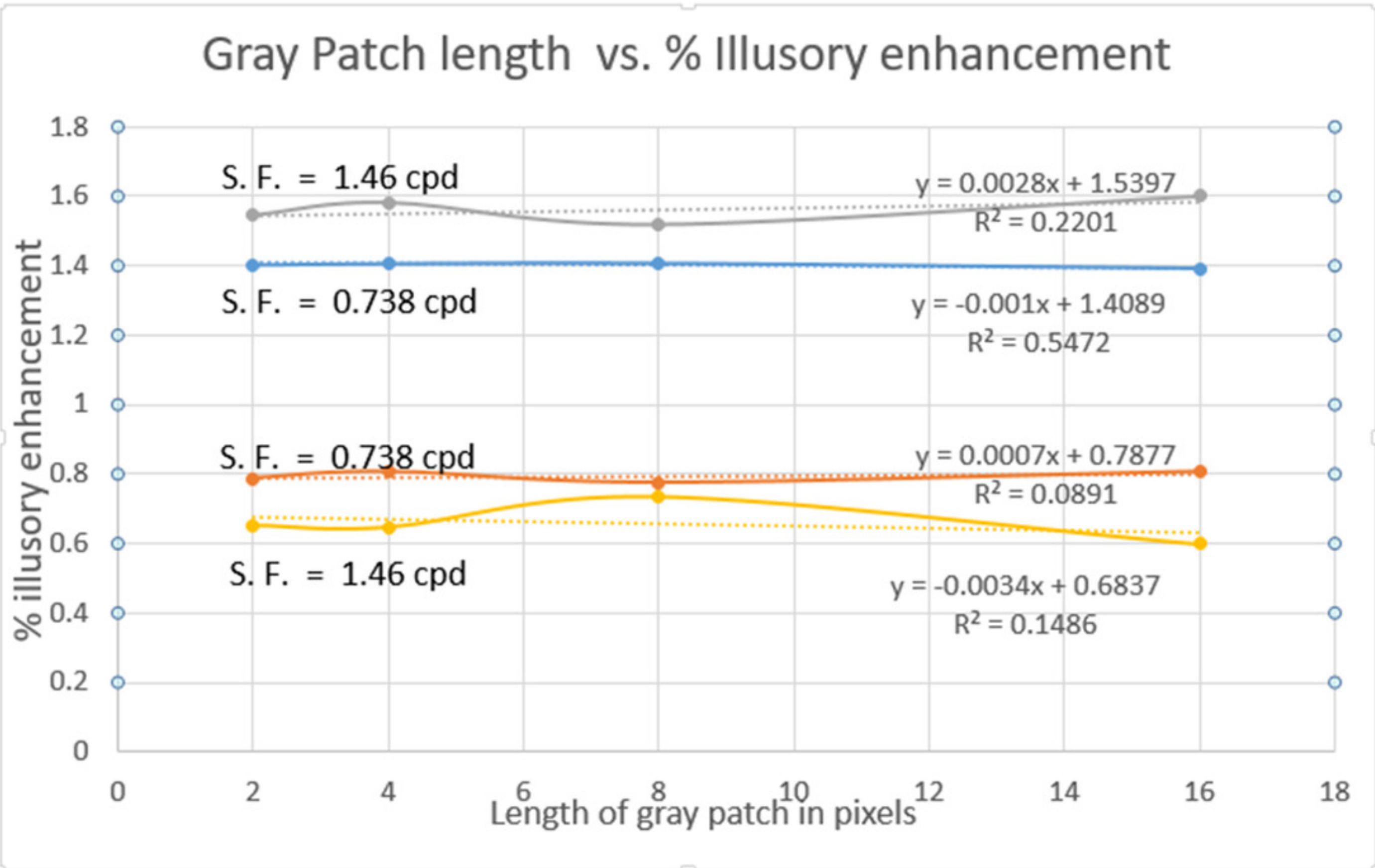

Figure 15

Variation of the scale factor of the Gaussian filter with grating frequency