

## Lightness of Munker-White illusion and Simultaneous-Contrast illusion: Establishing an ordinal lightness relation among minimum and split-frame presentations

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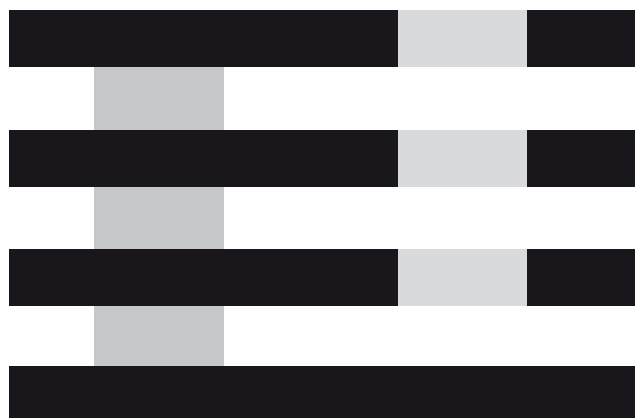
The achromatic Munker-White illusion and the Simultaneous-Contrast illusion have been used extensively in vision studies to understand how the figural configuration of a stimulus can affect the perceived lightness of its components in human perception. Yet, previous modeling and psychophysics studies did not directly compare the illusions' lightness with controlled parameters of minimum stripes and split-frame presentations, which are useful in testing model predictions and in correlating neural firings to final percept in electrophysiology. In our study, subjects performed lightness matching of the four minimum and split-frame presentations of the illusions. We found the lightness order from lightest to darkest to be statistically significant after normalization within each subject: SCB > MWW > SCW > MWB. This is to say that the lighter frame of Simultaneous Contrast (SCB) is lighter than the lighter frame of Munker-White (MWW), which is lighter than the darker frame of Simultaneous Contrast (SCW), which is still lighter than the darker frame of Munker-White (MWB).

*Key words:* Munker-White, Simultaneous-Contrast, lightness, illusion, psychophysics, spatial frequency, split-frame

Lightness illusions help us understand the essential strategies human vision employs to process surface properties. Luminance is the amount of light reaching the eyes from a surface. Lightness, on the other hand, is final perception after the convergence of innate visual mechanisms. Therefore, surfaces with the same luminance may have different perceived lightness. One such example is the Simultaneous-Contrast illusion (Chevreul, 1839), or SC, where a gray patch is perceived to be darker when surrounded by white than when surrounded by black. This can be explained by the low-level visual mechanism of lateral inhibition, where the surround of a receptive field either inhibits or excites the stimulation of the center in either an on-center or off-center structure.

Many other situations, however, cannot be explained by the lateral-inhibition mechanism. One such example is

the Munker-White illusion (Munker, 1970; White, 1981), or MW, where two identical gray patches are embedded in a field of alternating black and white bars (Figure 1).



*Figure 1.* The Munker-White illusion: The gray patches have the same luminance but those coaxial with black strips seem lighter. The illusion works in the opposite way in a simultaneous-contrast illusion. Since the right gray patches have longer borders with the white strips, and therefore lateral inhibition predicts that they should be perceived as darker.

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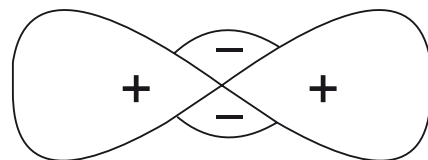
The target patches collinear with white bars are perceived to be darker than those collinear with black bars. The illusion works contrary to what the theory of lateral-inhibition alone predicts, because the former is surrounded by more black and the latter is surrounded by more white. This contradiction indicates that there are other mechanisms at work in MW besides lateral-inhibition. Other suggested mechanisms include the explanation of the role of boundaries in spatial luminance relationships (Spehar, Gilchrist, & Arend, 1995) and that of a perceptual scission which splits the contrast region along the junction of the T into multiple sources (Anderson, 1997). However, another study showed that the T-junctions contributed to the illusory lightness even in a three-dimensional configuration, which weakens the theory of perceived co-planarity or perceptual belonging inducing lightness (Zaidi, Spehar, & Shy, 1997). Anderson (1997) suggests that the T-junction theory is insufficient in explaining why the strength of MW is greater than that of SC under the specified parameters of the study. This is to say that the lightness difference between the pair of light and dark MW patches is larger than that of the SC patches. Further, studies done by Grossberg (1997) and Spehar et al. (1995) explain the phenomenon as a cooperative effect of geometry that generates figure-ground percept. In their studies, the stimuli used contain multiple gray patches instead of one. Grossberg explains that what is at work may be a case of occlusion, the perception of black stripes (or white) overlapping a continuous background of gray and white (or black) to generate a sense of depth that co-varies with lightness perception.

Several more recent studies on MW utilize different models with optimized parameters to more precisely predict the lightness of this visual illusion (Robinson, Hammon, & de Sa, 2007). Otazu's model (Otazu, Vanrell, & Párraga, 2008) reflects the effects of spatial frequency – a measure of the density of stripes in the surround – on lightness induction. Barkan, Spitzer, and Einav (2008) used a center-surround receptive field model with different grating parameters to define adaptation depending on the context of local and remote contrasts. Robinson et al. (2007) assumes an oriented receptive field that is elliptical, which serves as the basis for a “difference of Gaussian model” that utilizes a general filter and variable parameter gratings. To correctly and fully account for the strength and direction of lightness differences in MW, Robinson's model uses a localized normalization scheme that has the advantage of being more biologically plausible in representing early visual processing. In the same review paper, Robinson discussed that the illusion strength of SC with test patch sizes of  $3^\circ \times 3^\circ$  and  $1^\circ \times 1^\circ$  to be generally three times stronger than that of MW with test patch sizes of  $2^\circ \times 4^\circ$ ,  $1^\circ \times 2^\circ$ , and  $1^\circ \times 3^\circ$  (Robinson et al., 2007).

Further, Blakeslee, Pasiëka, and McCourt (2005) used a spatial filter to model illusions such as SC and MW and found that the mean lightness perceived for the MW pair

– presented together and with non-minimal stripe density – is lighter than the SC pair under similar conditions. This result differs from her previous study in 1999 and it is speculated that such a discrepancy may be attributable to changes in stimulation presentation. The matching patching was placed against a homogenous background in the 1999 study, whereas it was framed by a checkerboard boarder in the latter study after researchers found that subjects perceived the latter presentation to be easier in lightness matching.

Despite efforts made in previous studies, none directly compared MW and SC in their minimum and split-frame representations. By minimum, we mean that each MW contains one central gray patch flanked by a single pair of stripes on either side. In other words, there are no repeating stripes on either side of the patch as seen in most MW such as Figure 1. By split-frame, we mean that the two patches with opposing patterns of surround are shown separately, and each with its own adjustable patch for lightness matching. Our study with minimum and split-frame presentations is highly useful in testing models, such as one that is proposed by Ross and Pessoa (2000), in which multiple scales of filters and interactions are used. Another example is the one proposed by Kelly and Grossberg (2000) where the model implements bipole units that perform long range grouping and cross-orientation competition (Figure 2). In this case, a non-minimal stimulus would generate many additional groupings across edges resulting in complex interactions complicating the analysis of illusion strength, contributing to mechanisms such as figure-ground perception among others. Mechanisms of occlusion and figure-ground perception (Grossberg, 1997; Spehar et al., 1995) would be much reduced in the minimum case and therefore it is worth investigating MW's illusory strength comparative to SC under this condition. Minimum and split-frame images, therefore, contribute to verify the predictions of various models for the basic configuration of an illusory phenomenon. Further, this



LONG-RANGE COOPERATION  
(+) BIPOLE CELLS

SHORT-RANGE COMPETITION  
(-) HYPERCOMPLEX CELLS

Figure 2. Bipole cells provide long-range cooperation (+), whereas hyper-complex cells provide short-range competition (-) (Kelly & Grossberg, 2000)

most elementary form of illusions is also useful in electrophysiology in correlating neural firings with final lightness perception. The fewer non-essential elements that make up a stimulus, the fewer complex spike trains, and the easier it is to build a conclusive picture of the stimulus to response relationship.

## METHOD

### *Subjects*

We tested three subjects: one was author and two were naïve to the experiment. One subject was male. The age range was 20 to 35. All had either normal vision or corrected vision during experimentation.

### *Stimuli and procedure*

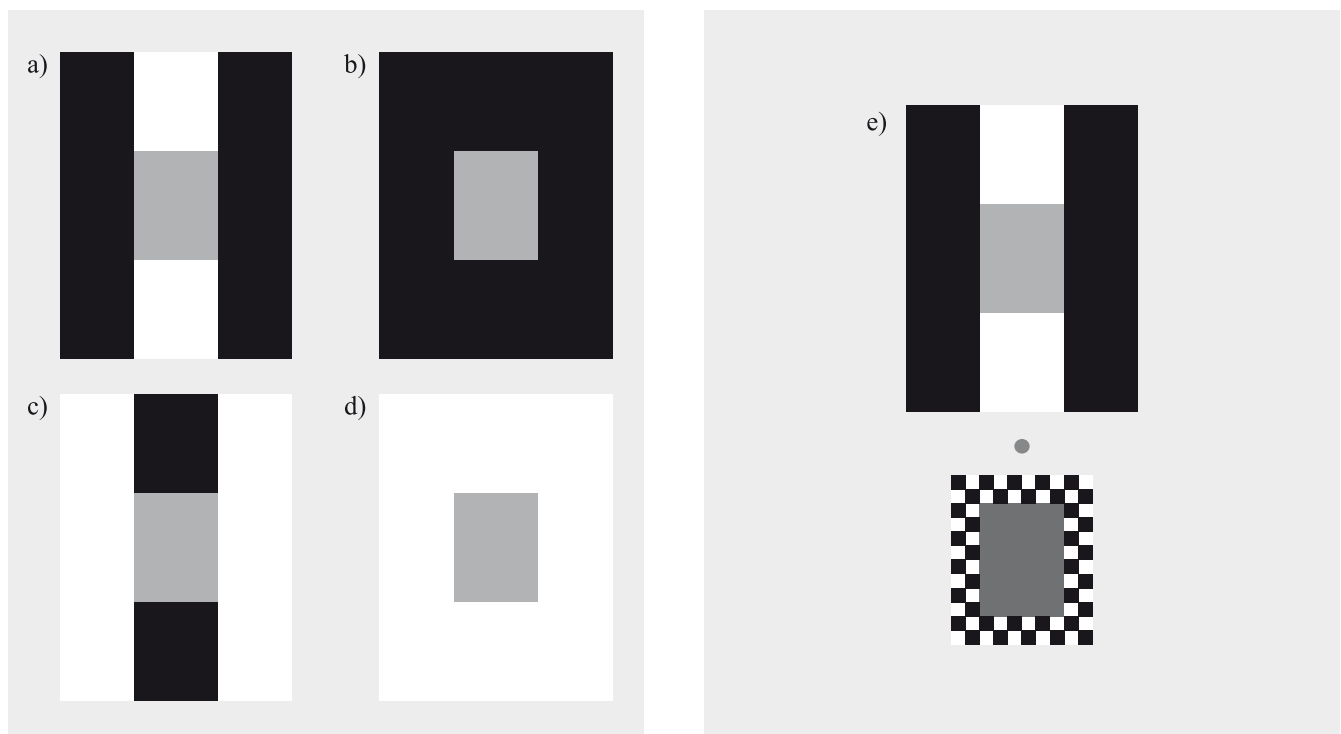
We presented each subject with four stimuli, each with one of the four minimum and split-frame images of MW and SC (Figure 3a-d) on the top, and an adjustable patch that is surrounded locally by a checkerboard on the bottom (Figure 3e as an example). The adjustable gray patch is identical in size to the gray patch in the illusory image. Subjects were

asked to fixate on a green dot at the center of the monitor, between the top and bottom items, while adjusting the luminance of the adjustable patch until its lightness matches that of the gray patch in the illusory image.

The minimum and split-frame images of MW and SC:

- 1) Rectangular gray patch is surrounded by black on the long sides and white on the short sides. This is Munker-White Black (MWB) (Figure 3a)
- 2) Rectangular gray patch is surrounded by uniform black. This is Simultaneous Contrast Black (SCB). (Figure 3b)
- 3) Rectangular gray patch is surrounded by white on the long sides and black on the short sides. This is Munker-White White (MWW) (Figure 3c)
- 4) Rectangular gray patch is surrounded by uniform white. This is Simultaneous Contrast White (SCW). (Figure 3d)

Presentations were made using MATLAB Psychtoolbox-3 and given on a LCD monitor with refresh rate of 60 Hz and maximum luminance of 150 cd/m<sup>2</sup> (measured by SpectraScan ® 650). Subjects were presented with the stimuli in a dimly lit room with consistent lighting conditions throughout the experiment. Stimuli were presented in four trials per subject per sitting and subjects were encouraged to close their eyes anytime during the experiment if they wish



*Figure 3.* The four images presented to subjects. a) Munker-White Black (MWB), b) Simultaneous Contrast Black (SCB), c) Munker-White White (MWW), d) Simultaneous Contrast White (SCW), e) an example of stimulus presentation: a split-frame (MWW) on top and adjustable gray patch on bottom. Other three presentations are in the same format with different split-frames as the image on top.

to rest them. Subjects were told to sit comfortably while maintaining an approximate distance of 60 cm away from the monitor. Subjects were also asked to fixate on a small green dot at the center of the screen and to blink frequently during lightness matching. They were not given a time constraint for this experiment.

The recorded lightness measures are on the grayscale from 0 to 255, corresponding to luminance of 0 to 150 cd/m<sup>2</sup> with a gamma correction of 2.4. The adjustable patch for each stimulus was initially set at a neutral luminance of 40.45 cd/m<sup>2</sup>, which is generally perceived to be slightly darker than any of the split-frame illusory images. Subjects were asked to adjust its luminance until its lightness matches that of the split-frame. They did so by pressing either the up or down key on the keyboard to increase or decrease, respectively, the luminance of the adjustable patch by 0.61

cd/m<sup>2</sup>. Subjects pressed the return key when they felt that they have achieved lightness matching. The luminance of the adjustable patch is then stored and the screen refreshed to show the next stimuli.

The checkerboard frame for the adjustable patch is modeled after Blakeslee's 2005 study design. We placed the adjustable patch on a 2° × 4° checkerboard background with each checker measuring 0.25° × 0.25° and the frame was 2 checkers thick on each side. We chose this pattern over a homogenous one because subject feedback from a trial run comparing the two conditions indicated that the checkerboard was easier to perceive, especially in performing lightness matching between the adjustable patch and SCB. The adjustable patch is affected by local decrement when the patch lightness is darker than the homogenous background, whereas SCB is affected by local increment.

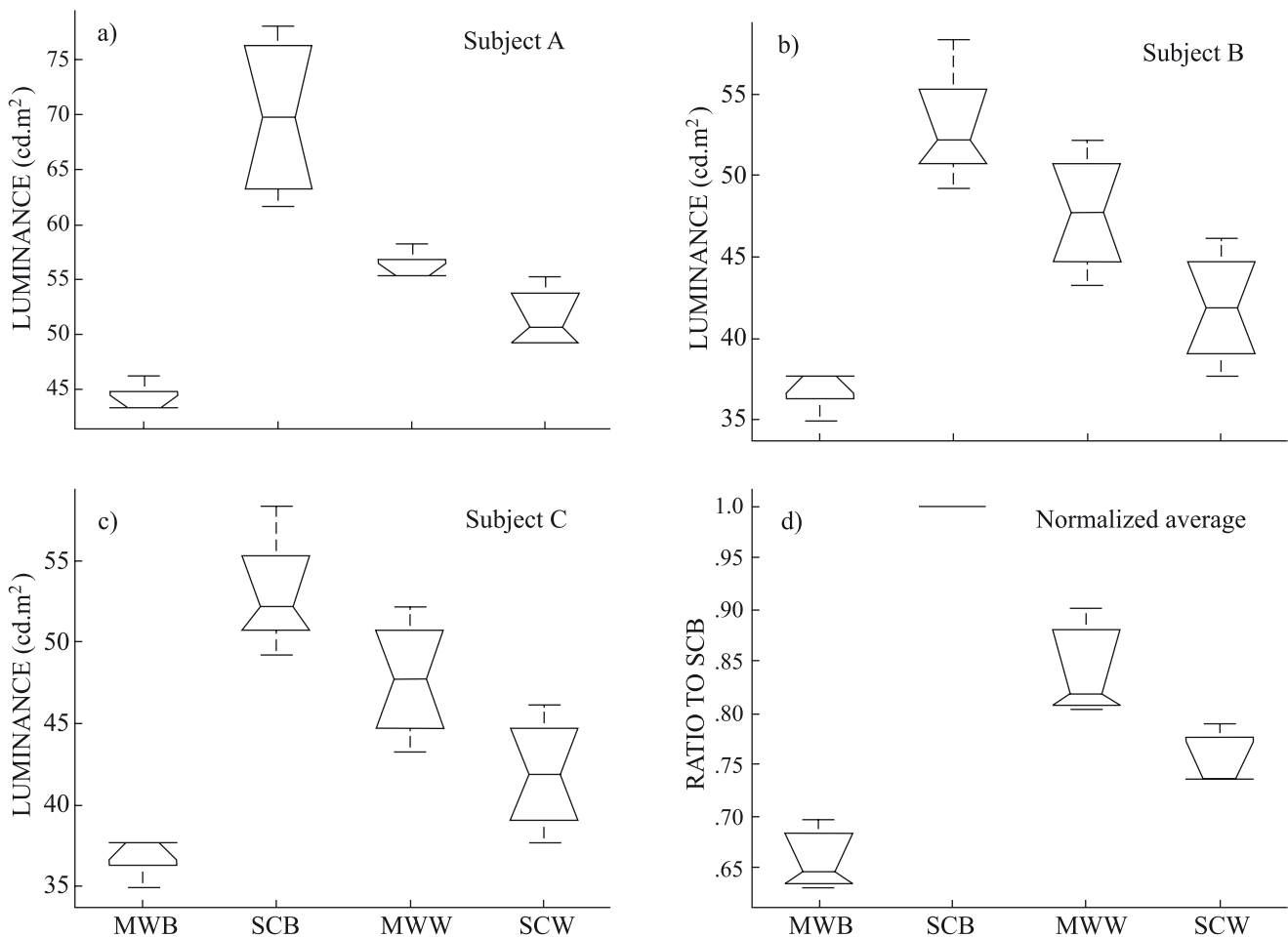


Figure 4. a) One-way ANOVA plot of subject A's lightness matching.  $F(3, 12) = 25.04, p < .0001$ , b) One-way ANOVA plot of subject B's lightness matching.  $F(3, 12) = 17.21, p = .0001$ , c) One-way ANOVA plot of subject C's lightness matching.  $F(3, 12) = 17.25, p = .0001$ , d) One-way ANOVA plot of the normalized averages of all three subjects.  $F(3, 8) = 51.33, p < .0001$ . Normalization was performed on each subject's average luminance values. All values were divided by the value for the lightest split-frame reported by each subject, which was invariably SCB.

## RESULTS

The ordinal relationship of the lightness perceived in the illusions is consistent across all subjects: SCB > MWW > SCW > MWB. The one-way ANOVA results from MATLAB indicate that the lightness differences in luminance measures are highly significant across split-frames for all three subjects (Figures 4a-c) — subject A:  $F(3, 12) = 25.04$ ,  $p < .0001$ ; subject B:  $F(3, 12) = 17.21$ ,  $p = .0001$ ; subject C:  $F(3, 12) = 17.25$ ,  $p = .0001$ . The conglomerate result across subjects is produced by taking the average luminance value of four trials for individual subjects and normalizing these averages to the luminance value the subject reported for SCB – the lightest split-frame. The ANOVA results for the normalized average lightness matching data also shows statistical significance of this ordinal lightness relation (Figure 4d):  $F(3, 8) = 51.33$ ,  $p < .0001$ .

## DISCUSSION

Motivated by demands of modeling testing and electrophysiology, we performed lightness matching of minimum and split-frame stimuli of the four MW and SC illusion images. Our results (Figure 4) show that under our controlled parameters of elementary stimulus presentation the ordinal lightness relation is: SCB > MWW > SCW > MWB. Further, ANOVA analyses of our normalized data across subjects show that on average, the luminance gap between the pair of minimum and split-frame SC patches is larger than that between the MW patches, indicating that SC is the stronger illusion.

Blakeslee and McCourt (2001) observed that the MW effect increases with increasing spatial frequency. In their study, the MW stimuli had a spatial frequency of 0.5 cycle/degree and there are several stripes on either side of the gray patch. Under these conditions, Blakeslee and McCourt found that the difference in illusion strength between SC and MW was statistically insignificant. If this trend persists in more extreme lower range of spatial frequencies, one can extrapolate from this study that in the minimum and split-frame conditions, SC would become the stronger illusion. This is indeed what we verified in our experiment. In our experiment, we used a spatial frequency of 0.33 cycle/degree, lower than the range used by Blakeslee and McCourt and therefore we should expect our MW to have a lower illusion strength based on their predictions. In fact, we found SC's illusion strength to be statistically higher than MW's. Our result therefore verified extrapolations from Blakeslee's 2001 study.

Our result supplements those from Blakeslee's studies in one other way as well. In Blakeslee and McCourt's 1999 study, the adjustable patch was placed on a homogenous background. Under this condition, subjects reported that SC is stronger than MW. A later study (Blakeslee et al., 2005) used a checkerboard background for the adjustable patch

and the results were reversed and not statistically significant. The previous finding was then believed to be byproducts of a background effect.

It is important to note that in our study examining the split-frames for SC and MW separately, we also found a local checkerboard frame to be the better presentation choice compared to a homogenous background. During the preliminary trials of our experiment, we investigated this effect by comparing subjects' feedback on lightness matching with both backgrounds. The homogenous background was set at a uniform luminance of 175 cd/m<sup>2</sup>, which is midway between minimum and maximum luminance levels for the monitor. Though the ordinal relationship was preserved in the homogenous condition, subjects produced highly variable lightness values for SCB and, to a less degree, for MWW as well. They reported that it was difficult to perceive this lightness difference on the homogenous background. This difficulty could be due to the fact that the adjustable patch is affected by local decrement when the luminance of the patch is darker than that of the homogenous background, whereas SCB is consistently affected by local increment.

There have been a number of models that account for lightness illusions, including Otazu et al. (2008), Robinson et al. (2007), and Barkan et al. (2008). Most of these models use the biologically plausible center-surround computational kernel. The major difference between these models is the use of parameters regarding size, adaptation dynamics, and the orientedness of units. These studies do predict the relative strengths of brightness illusions, including MW and SC, though not in the same study where the illusions were of the same size and spatial frequency. Our study directly compares the absolute strengths of the two illusions controlled for these parameters in establishing an ordinal lightness relation. Robinson et al. (2007) conducted a multi-scale comparative analysis of illusions, including MW and SC, and reported the illusion strengths under different parameters. The results confirmed our finding in all cases: the illusion strength between the SC pair is significantly higher than that between the MW pair. In fact, SC was invariantly much stronger than MW despite the size and parameter changes across the various studies: the strength between the SC pair ranges from 11.35 to 19.78 cd/m<sup>2</sup>, and the strength between the MW pair ranges from 4.18 to 6.43 cd/m<sup>2</sup>.

Our study under minimum and split-frame conditions produced the same ordinal relationship as those above-mentioned studies under different conditions. We, however, do not claim to generalize our finding to other dimensions and parameters as there may be size dependency in the split-frame presentation. By reducing the illusion to its minimal configurations, we prevented cooperative higher order effects, such as the influence of multi co-linear gray patches (Howe, 2001) and figure-ground geometry (Grossberg, 1997; Spehar et al., 1995) that are used to explain certain aspects of MW. Further, our second finding on SC's greater illusion strength under the specified parameters suggests that

the mechanism of lateral-inhibition distinguishing the gray patches in the SC illusion in this case can be more dominant over the second -order mechanism distinguishing the two in MW illusion. This result can be used as a quantitative basis for any electrophysiological study that seeks the neural correlate of the Munker-White Illusion. For example, by registering the firing rate of cells of receptive fields within the gray patches and comparing them with the quantitative perceptual finding here, the first step toward uncovering the interplay between the subjective and neural correlate of lightness perception could be measured. Furthermore, these results can be used in modeling studies to further restrict boundary constraints, parameter space, and circuit connections in the models.

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