Perceived lightness difference with regard to spatial frequency and amplitude modulation

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ABSTRACT

It has been found that the L^* function defined in the CIELAB color space is not suitable to predict the human visual perception of modulated patterns at high spatial frequencies. For example, in multilevel halftoning (multitoning), when output levels are equally spaced in L^*, it has been observed that the visibility of the resulting multitone patterns is not uniform across different parts of the tone scale. This leads to the hypothesis that the CIE L^* function may not be a good metric to evaluate the perceived lightness differences at high-spatial frequencies as it was derived based on the perception of large area uniform patches. To investigate the relationship between suprathreshold lightness difference perception with regard to spatial frequency and amplitude modulation, we designed a psychophysical experiment, which was conducted using a lightness difference matching paradigm. The stimuli used in the experiment were horizontal square-wave gratings. The behavior of lightness difference perception under varying spatial frequencies and modulation amplitudes across the entire L^* scale was studied. Consistent results were acquired that show a significant frequency-dependent effect where the effective lightness difference for high-frequency patterns is reduced for low L^* values. The magnitude of this effect was found to be highly related to the spatial frequency of the modulation. Based on these results, we derived an effective lightness function that is dependent on spatial frequency. The effective lightness function can be applied to the selection of the output levels for multitoning.

Keywords: perceived lightness difference, CIE L^*, spatial frequency, amplitude modulation, multitone

1. INTRODUCTION

The brightness perception of the human visual system to luminance is not linear, and can be approximated using a power-law function. The L^* function defined in CIELAB color space was designed to be linearly related to the human visual perception to luminance.[1] A patch with an L^* value twice that of a reference patch would be perceived to be twice as bright as the reference patch. Similarly, equal differences in L^* values would result in equal differences in brightness perception. Because of its linear and uniform relation with visual perception, L^* is widely used in many digital imaging applications. However, there are some limitations in applying L^* function. The L^* function was developed based on the estimation of perceived lightness of large area uniform patches. Experimentally, it was observed that the L^* function may not be suitable to characterize the perception of lightness differences for applications where the stimuli are presented at high spatial frequencies. For example, multitoning is a technique that uses black, white, and one or more middle gray levels to produce the appearance of continuous tone images. The lightness of the intermediate output levels will have a direct effect on the visibility of the resulting multitoning patterns. If the output levels are chosen to be equally spaced in L^* space, we would expect to obtain results where the perceptibility of the multitoning levels would be independent of lightness level. However, experimental results have shown that the visibility of the modulation for a gray ramp produced by this method is not uniform. In particular, the multitone patterns are more visible at high L^* values than at low L^* values.[2] This result suggests that lightness difference perception is related to the frequency content of the stimulus as well, and therefore that the L^* function defined in CIELAB color space may not be a good measurement of perception at high frequencies. Thus, the understanding

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of the perception of lightness difference at high-spatial frequencies is essential for high-quality multitone reproduction. Little research has been reported to study the behavior of human lightness difference perception under high spatial frequencies. Based on the above considerations, we designed a psychophysical experiment to investigate suprathreshold lightness difference perception for modulated signals as a function of spatial frequency and amplitude. Our particular interest is to define an effective L^* space based on the experiment that can be applied to the selection of the output levels for multitoning. The resulting multitone patterns are expected to have uniform visibility across the tone scale.

2. EXPERIMENT

2.1. Apparatus

The stimuli were presented on a 20-inch Barco monitor. The scan mode of the monitor was non-interlaced. The resolution of the monitor was 1152 by 900. The monitor was characterized using a tele-spectral-radiometer at 14.2 feet from the monitor, which was the distance that the subjects observed the monitor during the experiment. The measured luminance was converted to L^* value and a look-up table from code value to L^* value was generated.

The formula used to convert luminance to lightness is:[1,3]

$$L^* = \begin{cases} 116(Y/Y_n)^{1/3} - 16; & \text{if } (Y/Y_n) > 0.008856 \\ 903.3(Y/Y_n); & \text{otherwise} \end{cases} \tag{1}$$

where Y is luminance and Y_n is the luminance of the white point of the monitor.

2.2. Subjects

Five observers participated in this experiment. Three of the authors, MW, QY and RM, took part in the experiment and MW repeated the experiment twice. The other two observers were HL (an experienced observer), and SD (an inexperienced observer). Both HL and SD were not knowledgeable of the design of the experiment.

2.3. Procedures

The experiment was conducted using a lightness difference matching paradigm. The stimuli used in the experiment were horizontal square-wave gratings with variable spatial frequencies and modulated lightness amplitudes. The task of the observer was to compare the perceived lightness modulation of a standard patch to that of a test patch, and to adjust the amplitude of the modulation of the test patch until an equal perceived lightness modulation was acquired. The standard patch and the test patch each subtended a visual angle of 2° at the observing distance of 14.2 feet. The stimuli were displayed in a complex field that consisted of randomly placed squares with random sizes and gray levels. This complex background reduces the effect of global adaptation and edge effects on the lightness modulation perception. The mean luminance of this random background pattern was 21.1 cd/m^2. The square-wave pattern was blurred near the boundaries of the patches. The blurred edges and the complex background helped to reduce the effect of the contrast between the target and the background. The gratings and the complex background are illustrated in **Figure 1**.

The observers viewed the monitor binocularly in a dark room. The experiment began after several minutes of the adaptation of the dark surroundings and a short practice session. The observer was allowed to take a short break between the sessions if he or she felt fatigue. The average time to complete the entire experiment was one and a half hours.

The entire experiment was divided to three sessions. In each session, the perceived lightness modulation for a given amplitude was examined at three different spatial frequencies. The average lightness value of the standard patch was set at $L^* \cong 50$, and the amplitude of the lightness modulation for the standard patch was set to 6.39, 12.7, and 25.5 L^* units for the three sessions, respectively. These differences corresponded to about 1/16, 1/8, and 1/4 fractions of the entire L^* range. The three spatial frequencies were: DC (0 pcd), 8 *cpd,* and 12 *cpd* for the lowest amplitude ($\Delta L^* = 6.39$); DC, 8 *cpd,* and 15 *cpd* for the intermediate amplitude ($\Delta L^* = 12.7$); and DC, 12 *cpd* and 20 *cpd* for the highest amplitude ($\Delta L^* = 25.5$). The "DC" case indicates bipartite patches that were used to verify the lightness difference perception of solid patches. The adjustment in the spatial frequencies for different amplitudes was introduced to ensure that the patterns remained suprathreshold, while exploring the largest possible frequency range.

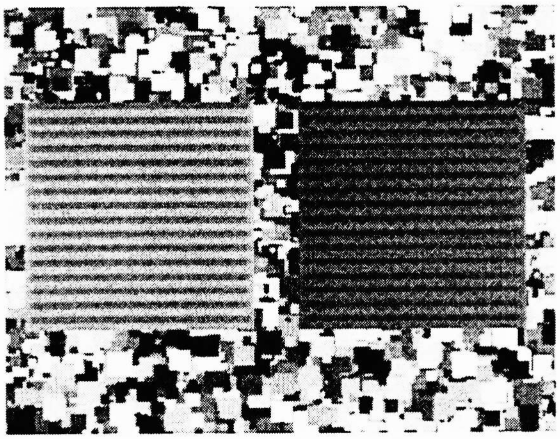

Figure 1. Illustration of the complex background and the stimuli. The grating on the left is the standard patch and grating on the right is the test patch.

Within each session, the standard gratings maintained the same average L^* and ΔL^* values and varied only in spatial frequency. Each session comprised of three sub-sessions where each sub-session tested one of the spatial frequencies. A standard patch with a predetermined lightness difference and spatial frequency was presented, together with a test patch having the same spatial frequency, but with a different average L^* value. The average L^* value of the test patches varied across the entire lightness scale. The matching was always conducted between the gratings with same spatial frequency. The initial lightness modulation of the test patches was chosen to be equal to the ΔL^* of the standard patch plus a randomized difference, which could be either positive or negative. Test patches were first presented in ascending lightness order, and then in descending lightness order. For each test patch, the observer adjusted the amplitude of the lightness modulation until it matched the perceived lightness modulation of the standard patch. The observer used the keyboard to adjust the amplitude of the lightness modulation for the test patch. The up and down arrow keys were used for large adjustments (± 5 L^* units), and the left and right arrow keys were used for small adjustments (± 1 L^* unit). After each test patch was presented twice, the differences between the matched amplitude values were calculated, and patches that resulted in high variations were tested one more time to reduce the uncertainty of the data.

Preliminary experiments showed that it was more difficult for the observers to judge the modulation of patterns with large lightness differences, so the session for the smallest ΔL^* was done first and the session for the largest ΔL^* was done last. Through the "practice" in the earlier sessions, the observers became more experienced and thus they were able to give more accurate estimations for the larger amplitude session. Arranging the patterns with close ΔL^* in adjacent trials also reduces the effect of pattern adaptation which can occur in an abrupt change of contrast.[4]

3. RESULTS AND ANALYSES

The results of all the six observations are plotted in **Figure 2** to **Figure** 7. In total, there were six observations from five subjects. The x-axis in each figure is the average lightness L^* of the test patches, and the y-axis is the resulting lightness amplitude, ΔL^*, of the test patches having the same perceived modulation as the standard patch. The spatial frequencies and reference amplitudes (ΔL^* of the standard patch) associated with the data are labeled in each figure. In each figure, there are three groups of curves, each comprised of three curves. From the top to the bottom, each group of curves represents the results from the largest ΔL^* to the smallest ΔL^*, respectively. The results for DC of all the three sessions are plotted as solid lines, those of the middle frequencies are plotted as long dashed lines, and those of the high frequencies are plotted as short dashed lines. A point at a particular position (L^*, ΔL^*) indicates that a pattern with an average lightness of L^* and a lightness difference of ΔL^* produced the same perceived lightness modulation as the standard patch at certain spatial frequency. We call the perceived lightness difference as the effective lightness difference ΔL_e^* because the lightness differences of the matched patches were effectively perceived equal. All the points on one curve had same ΔL_e^*. Thus the curve reflects the relationship between the perceived lightness difference and L^* values at the given frequency and amplitude.

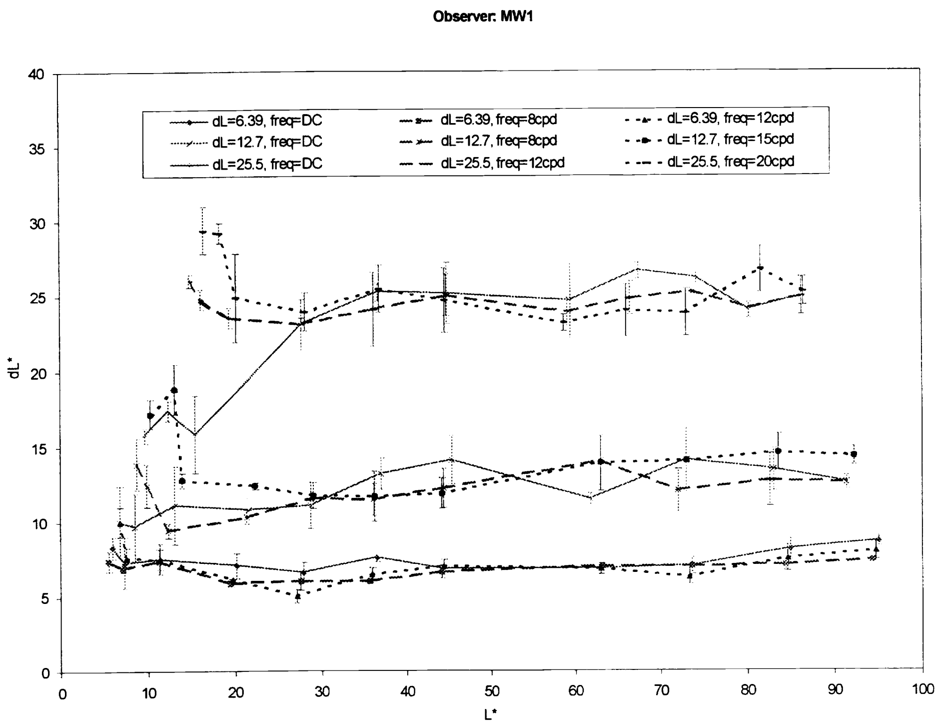

Figure 2. Result of the subject MW, the first trial.

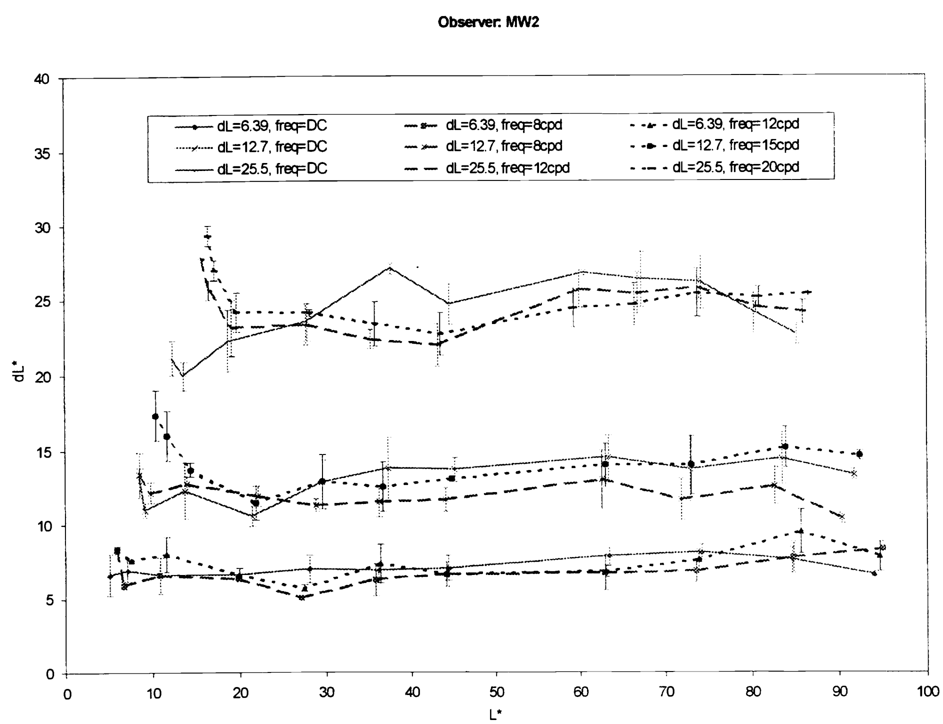

Figure 3. Result of the subject MW, the second trial.

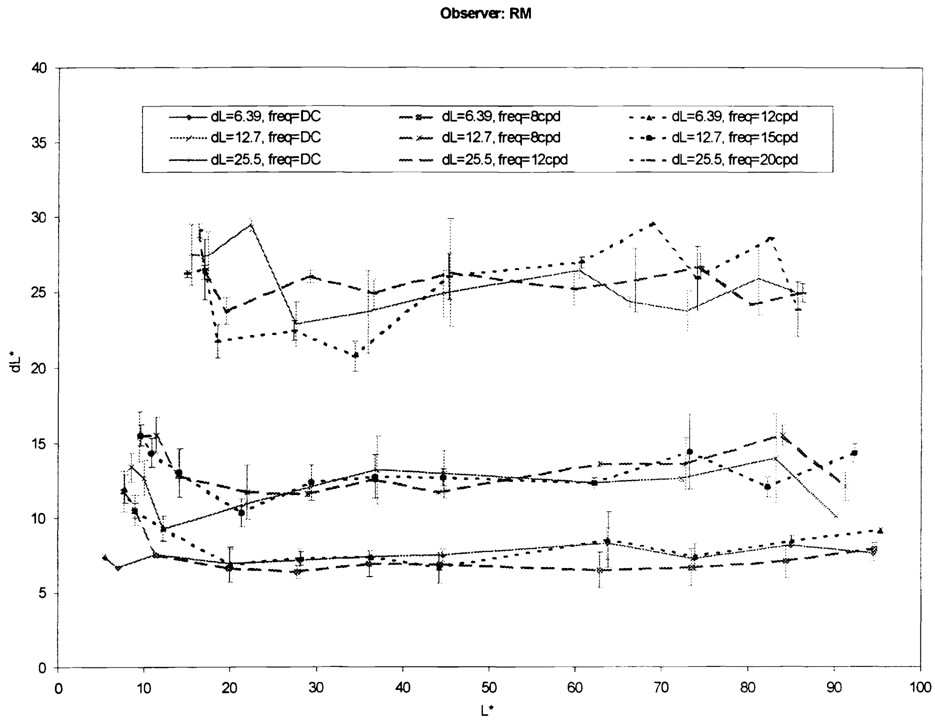

Figure 4. Result of the subject RM.

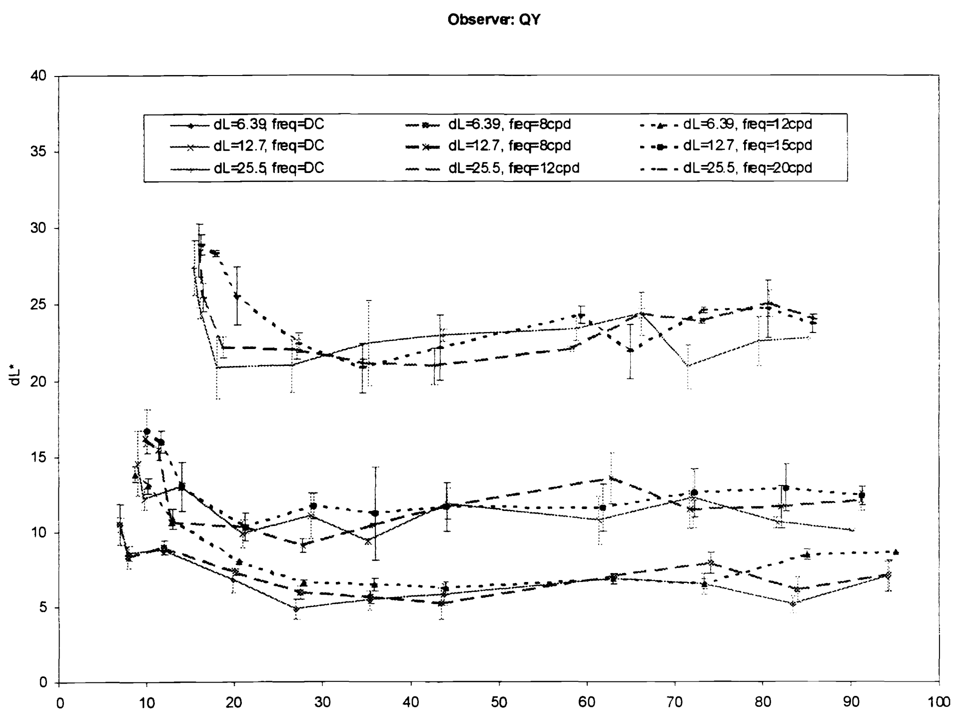

Figure 5. Result of the subject QY.

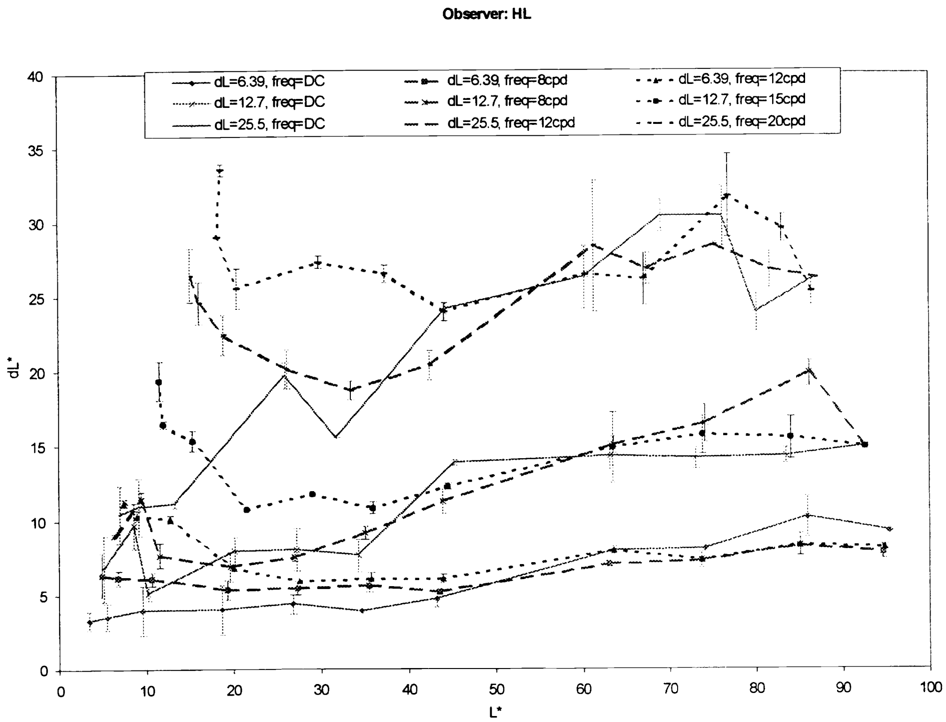

Figure 6. Result of the subject HL.

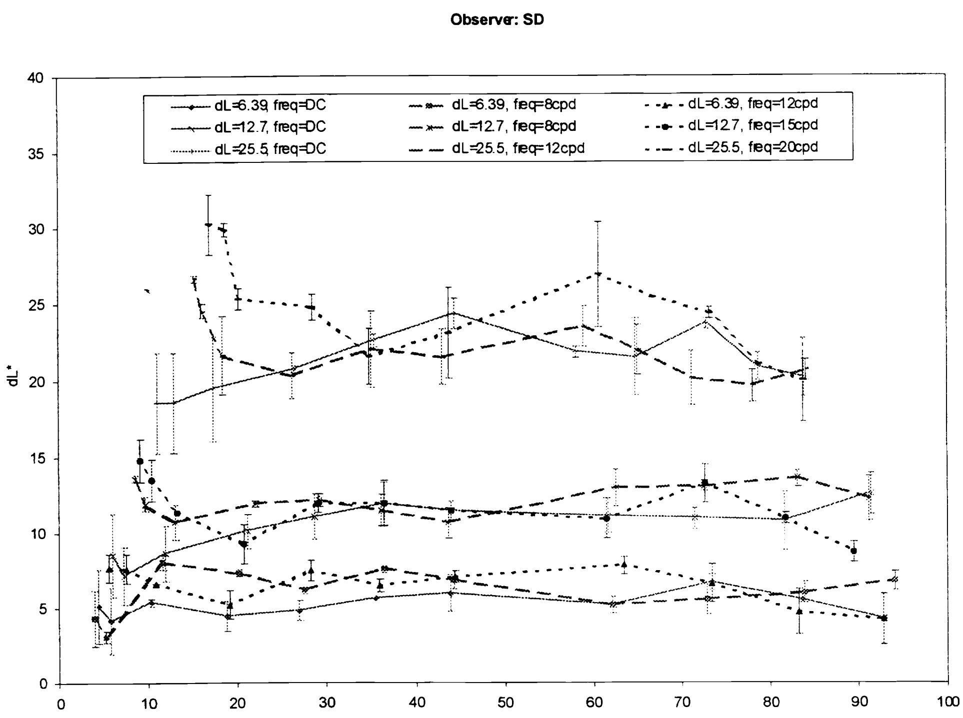

Figure 7. Result of the subject SD.

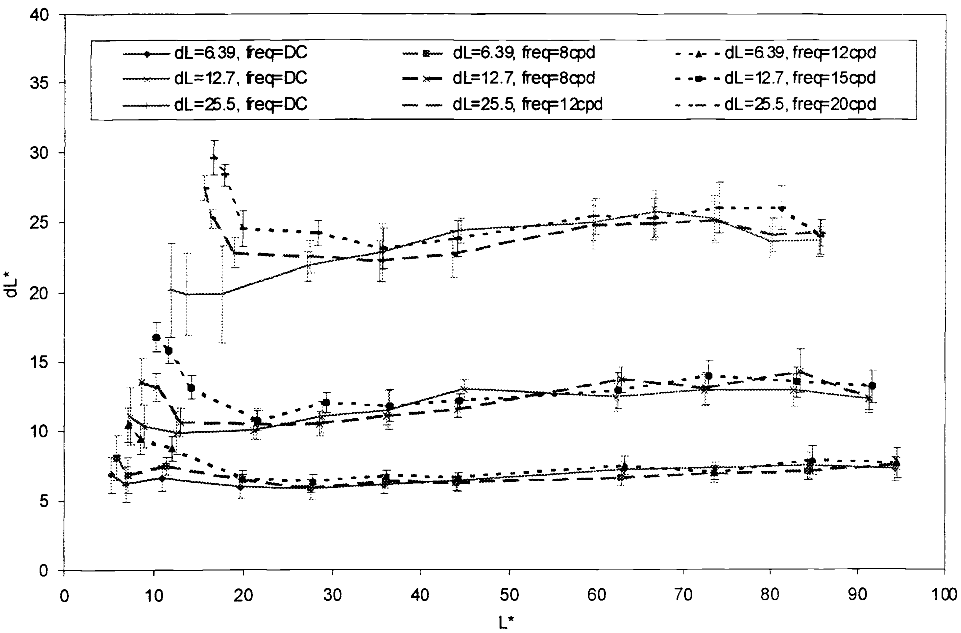

Figure 8. Average response of the six observations.

Several observations can be made upon examination of this data. First, all the high-frequency curves (long dashed lines for small frequency values and short dashed lines for large frequency values) bend upward for low L^* values ($\sim L^* < 30$). Generally, the curves bend more for higher frequencies and larger modulation amplitudes. Second, there was no obvious trend at higher L^* values, where the curves tend to be relatively flat.

For the DC case, the variations between observers were significantly larger than those for higher frequencies. The DC curves for four observations (MW1, MW2, HL, and SD) bend in the direction that is opposite to the high frequency lines, especially for ΔL^* equal to 12.7 and 25.5, whereas those of the other two observations (RM and QY) bend in the same direction as the high-frequency lines. This reflects the fact that most subjects indicated that it was difficult to judge the amplitude of the bipartite patches in the experiment, especially when the ΔL^* was large.

The mean response and variations of the six observations are plotted in **Figure 8**. The curves for different frequencies were statistically different at low L^* values ($\sim L^*<30$). It can be easily observed that there is a trend from DC to high frequencies in the low L^* region. The curves for different frequencies are separated and arranged in the order of the frequency values. The higher the frequency is, the further it is apart from the flat line, indicating the frequency effect on lightness difference perception. The upward bending of the high-frequency curves means that, in order to produce the same effective ΔL^* as the patch with high average L^* value, a larger ΔL^* must be used for patches with low average L^* value. In other words, the effective lightness difference is reduced at low L^* values under high frequencies. The magnitude of the effect is larger for higher frequency. A similar phenomenon was reported by Peli *et al.*, where the low pass characteristic of apparent contrast was found at low luminance levels.[5] The observed effect of reduced effective lightness difference at low L^* is consistent with the fact that was found in the multitone experiment, where the halftone patterns are more visible at high L^* than at low L^*.[2]

It is also interesting to note that the DC curves were not strictly horizontal lines, as that would be expected according to the prediction of L^*. The observers showed different behaviors in matching ΔL^* of the DC patches. The deviations are larger for larger ΔL^* values. One possible reason for this could be that the viewing conditions (such as illuminance level, background luminance level and the areas of the stimuli) are not identical to those under which the lightness function was originally derived.

Based on the experimental results, we further derived the derivatives of the effective lightness L_e^* vs the conventional lightness L^*. The experimental data marked by same legend had equal effective lightness differences. Suppose for one group of data, the matched patches were (L_1^*, ΔL_1^*), (L_2^*, ΔL_2^*), ..., (L_n^*,ΔL_n*), and their effective lightness differences ΔL_e^* were ΔL_{e1}^*, ΔL_{e2}^*, ..., ΔL_{en}^*, respectively. Since all the patches had same perceived lightness differences as the standard patch, we have:

$$\Delta L_{e1}^* = \Delta L_{e2}^* = \cdots = \Delta L_{en}^* = \Delta L_{e0}^* \tag{2}$$

where the number 1 to n denote the serial numbers of the measured data and ΔL_{e0}^* is the effective lightness difference of the standard patch. Furthermore, the differentiation of L_e* vs L^* at L_l^* $(l = 1, 2, ..., n)$ can be approximated by:

$$\frac{dL_e^*}{dL^*}(L_i^*) \approx \frac{\Delta L_{ei}^*}{\Delta L_i^*} = \frac{\Delta L_{e0}^*}{\Delta L_i^*} \tag{3}$$

Because ΔL_{e0}^* is an undetermined constant in each particular session, the differential equation can be expressed by:

$$\frac{dL_e^*}{dL^*} = cons. * \frac{1}{\Delta L^*} \tag{4}$$

Using the above equation, we plotted the first-order derivative of L_e^* vs L* for the three amplitudes, ΔL^* = 6.39, 12.7 and 25.5, under varying frequencies. For these plots, the constant in the differential equations was chosen to be the ΔL_0^* of the standard patch. **Figure 9**, **Figure 10**, and **Figure 11** illustrate the approximated dL_e^*/dL^* based on the experimental data for ΔL^*=6.39, 12.7, and 25.5, respectively. The measured data were plotted as isolate points in the figures, together with associated error bars. Then we fitted the isolated points with smooth curves. The functional form used for the curve fitting was:

$$f(\frac{dL_e^*}{dL^*}) = (a_1 + a_2 L^*)(1 - a_3 \exp(-a_4 L^{*2})) \tag{5}$$

where a_1 is a general factor, which controls the small drift of the function around 1, a_2 is used to take account into the slight drop of the derivatives at high L^* end, a_3 describes the degree that the curve deviates from 1at low L^* end, and a_4 influences the position of the transition from reduced lightness difference perception to normal lightness difference perception. The fitted curves are plotted in the same figures.

Finally, the relationship between the effective L_e^* and the conventional L^* was obtained by performing a numerical integration of the derivative functions plotted in **Figure 9** to **Figure 11**. Boundary conditions were applied so that L_e^*=0 when L^*=0, and L_e^*=100 when L^*=100. The resulting mappings from L^* to L_e^* are plotted in **Figure 12**, **Figure 13**, and **Figure 14**, respectively.

The influence of amplitude modulation for a constant frequency is also of interest. The characteristics at a frequency of 8 *cpd* were studied at ΔL^*=6.39 and ΔL^*=12.7, and the characteristics at a frequency of 12 *cpd* were studied at ΔL^*=6.39 and ΔL^*=25.5. The effective lightness spaces under these conditions are replotted in **Figure 15**. It can be seen that the two curves of 8 *cpd* are hardly distinguishable and the two curves of 12 *cpd* are also very close. This suggests that there is no significant effect of the amplitude modulation on the perception of lightness differences at frequencies examined in this study.

4. CONCLUSIONS

The objective of this work was to study the visual behavior of perceived lightness difference as a function of spatial frequency and amplitude modulation. For high frequencies, it was found that the perceived lightness difference was reduced at low L^* values, whereas no significant effect was observed at large L^* values. Furthermore, an "effective lightness" space

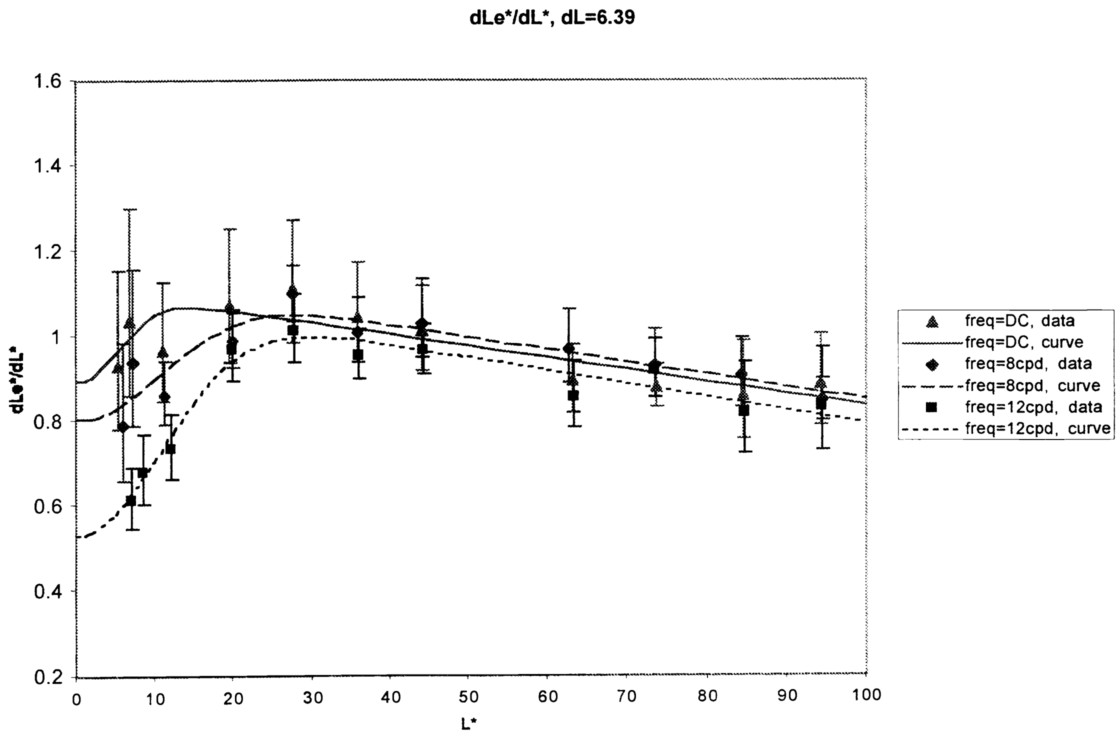

Figure 9. dLe^*/dL^*. Experimental data and fitting curve for ΔL^*=6.39.

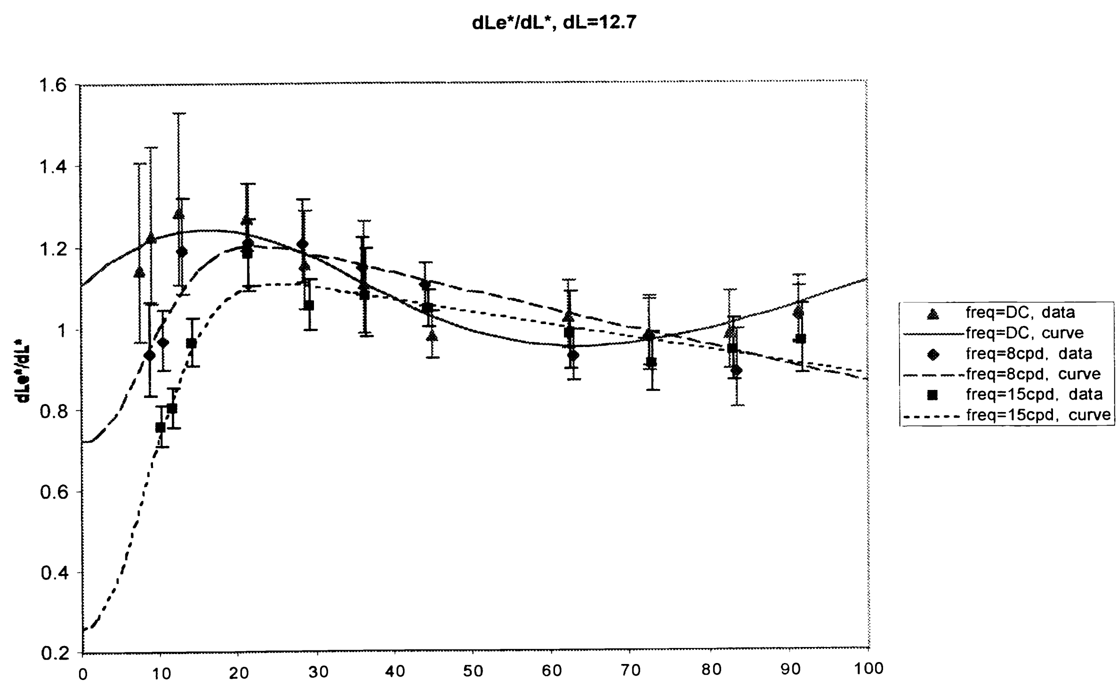

Figure 10. dL_e^*/dL^*. Experimental data and fitting curve for ΔL^*=12.7.

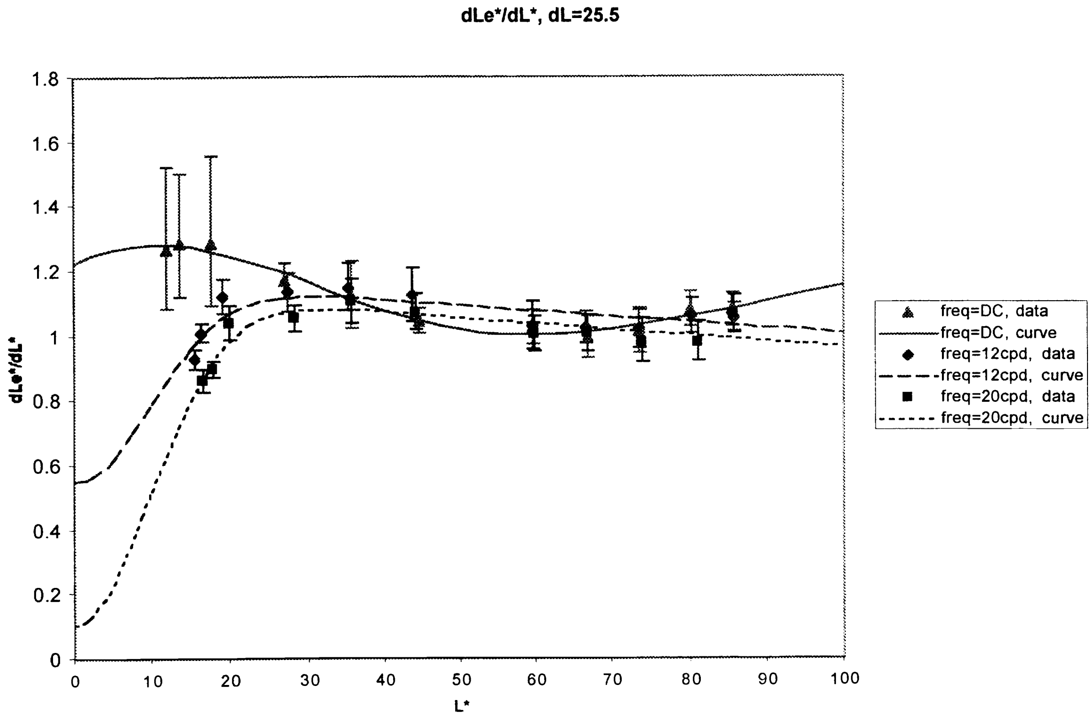

Figure 11. dLe^*/dL^*. Experimental data and fitting curve for ΔL^*=25.5.

was derived based on these experimental results. By comparing the effective lightness functions that are related to different frequencies and amplitude modulations, we conclude that perceived lightness difference highly depends on the frequency, whereas the amplitude of the modulation has little effect. We intend to apply the effective lightness space to multitone application in future research.

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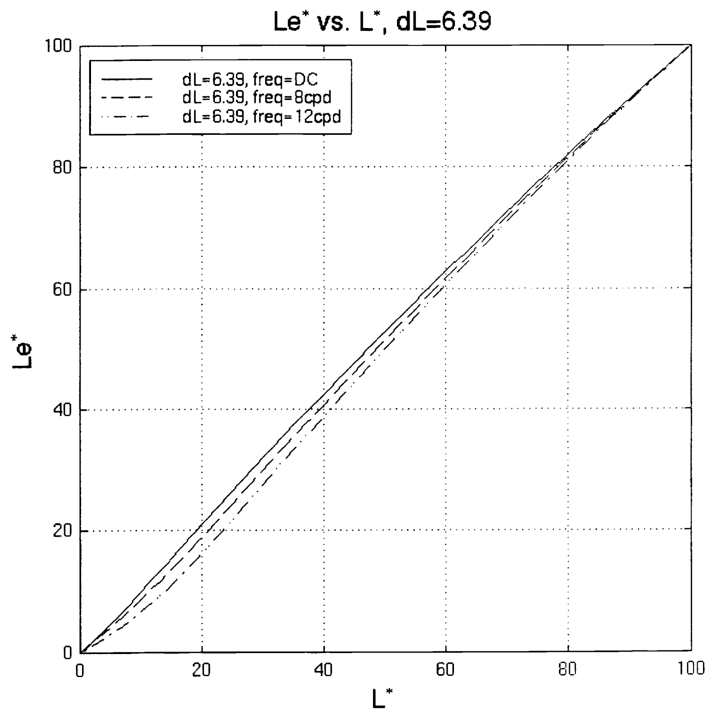

Figure 12. L_e^* vs L^*. ΔL^*=6.39.

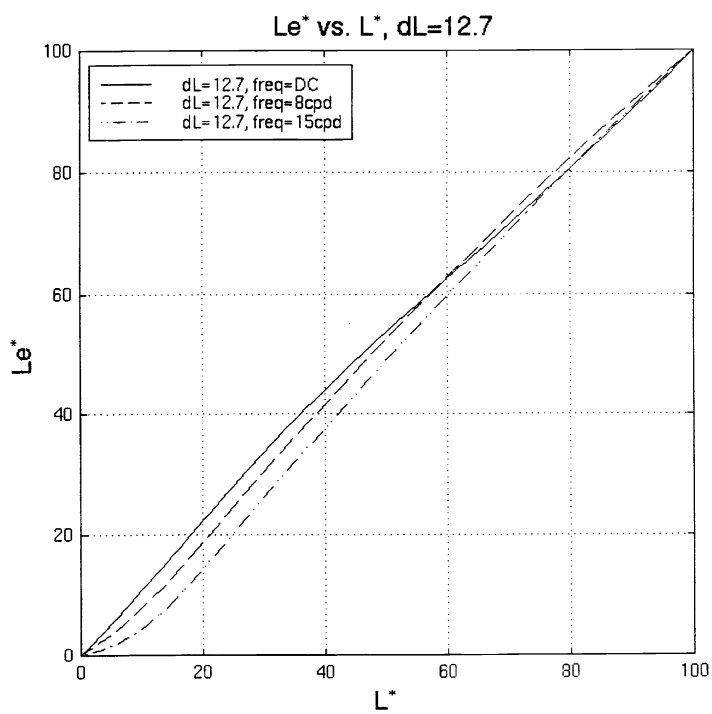

Figure 13. L_e^* vs L^*. ΔL^*=12.7.

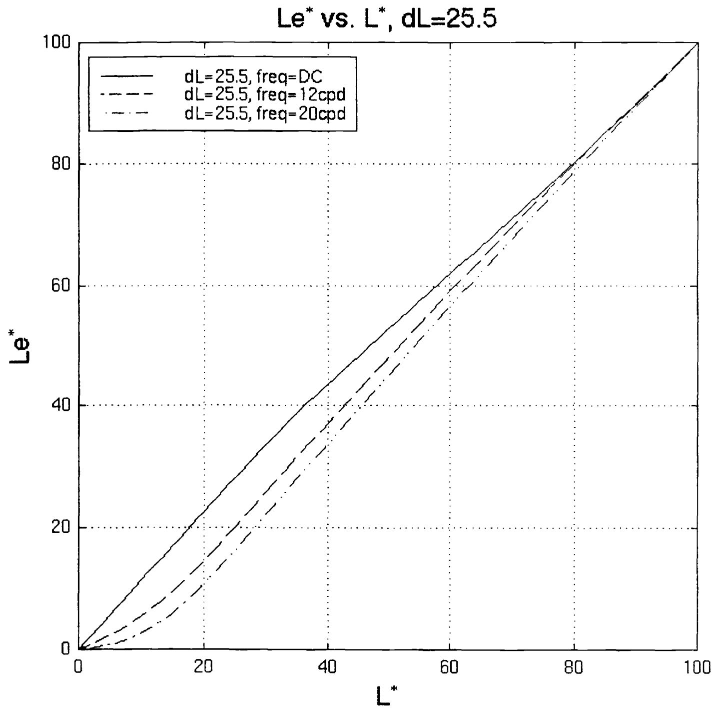

Figure 14. L_e^* vs L^*. ΔL^*=25.5.

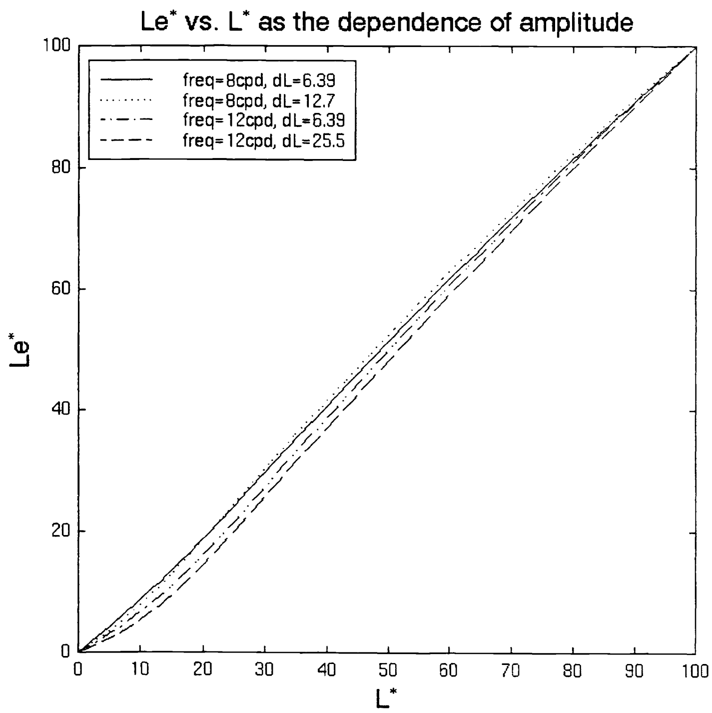

Figure 15. L_e^* vs L^* under frequencies 8 *cpd* and 12 *cpd* at various amplitude modulations.