Colour Appearance of Room Colours

Kaida Xiao, M. Ronnier Luo,* Changjun Li, Guowei Hong

Department of Colour Science, University of Leeds, Leeds LS2 9JT, United Kingdom

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Abstract: Psychophysical experiments were conducted to investigate the colour appearance changes between small colour patches and real room colours. The results clearly showed that colours appear lighter and more colourful for room colours. A method based on CIECAM02 was developed to quantify the colour size effect. © 2010 Wiley Periodicals, Inc. Col Res Appl, 35, 284 – 293, 2010; Published online 15 January 2010 in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.20575

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INTRODUCTION

A typical problem that has been experienced long by the paint manufacturers is that the paints purchased in stores usually do not appear the same after they are painted onto the walls in a room. This phenomenon of colour appearance change also causes great difficulties for homeowners, interior designers, and architects when they select colour ranges. Furthermore, there is also a strong demand from imaging industry to understand the changes of colour appearance due to different sizes of displays in order to faithfully reproduce or enhance the natural scenes on a larger size of display/TV.

Colour appearance models[1,2] have been extensively applied to cross-media colour reproduction across different imaging media under difference viewing conditions because its colour appearance attributes, such as, lightness, colourfulness, and hue are independent of various viewing conditions. In order to predict accurately the colour appearance of colours under a wide range of viewing conditions, CIE TC8-01 recommended the use of CIECAM02 colour appearance model,[3] which is based on CIECAM97s[4] and incorporates a number of new revisions and simplifications.[5,6]

*Correspondence to: M. Ronnier Luo (e-mail: m.r.luo@leeds.ac.uk).

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With the above in mind, International Commission on Illumination (CIE) established a technical committee, TC1-68 *Effect of stimulus sizes on colour appearance* with the aim to compare the colour appearance of small ($<2^\circ$) and large ($>20^\circ$) uniform stimuli on neutral background.

This study is aimed to investigate the colour size effect and to model the effect by fitting the present experimental results. Nevertheless, the direct use of CIECAM02 colour appearance model still cannot produce satisfactory results due to two remaining issues: size effect and reflected light in a room condition. Size effect refers to the colour appearance phenomenon that a surface colour appears different when the size of the colour changes. The conventional method for predicting colour appearance[7] can be applied effectively only for colours in a relatively small size (ca. 10° viewing size or below) instead of a large colour area, such as, room size (up to 50° viewing size). In other words, the current colorimetric data does not take size effect into account and, therefore, the appearance of room size colours cannot be successfully predicted. The other key factor is that the overall lighting condition in a real room is more complicated than that of a standard viewing cabinet as the lighting in a room is not only affected by the colour of the illuminant but also the reflected light from the coloured walls. Thus, when the walls are painted in various colours, the overall lighting will change accordingly. Therefore, the definition of room colour in this study does not only refer to its large size but also the viewing condition in a real room situation.

Kutas *et al*.[8,9] conducted an experiment to investigate colour size effect using displays, in which the colour appearance of large homogeneous stimuli ($85^\circ \times 55^\circ$) displayed on a plasma display were matched by smaller patches (2° and 10°) on a CRT display. Their experimental results represented by CIELAB colour attributes, showed that there is a significant colour size effect, that is, stimuli appear lighter for larger size, but no sign of colourfulness increase and little hue changes.

Billger[10,11] was probably the first to carry out colour appearance studies of large size colour in a real room condition. In her study, a number of colours were painted in different areas of an experimental room and assessed by psychophysical experiments. Colour appearance assessment techniques including magnitude estimation and asymmetric colour matching were adopted and their performances were compared. She found that the technique of indirect matching (asymmetric colour matching) using NCS[11] colour samples in a viewing cabinet or a reference box would achieve a more reliable experiment results than the magnitude estimation technique.[12] She also discovered significant adaptation effect when the light source in a room was different from the light source in a viewing cabinet or reference box. She observed that comparing with small size colour chips, room colours were perceived stronger in colourfulness. The work of Stahre *et al.*[13] addressed the same issue of colour appearance change between a small size colour chip and the same colour applied to a real room. They reached the same conclusion that room colour became higher in NCS chromaticness and blackness values. Harleman[14] investigated the difference between the colour appearances of a room colour under different lighting conditions by using a colour matching technique. She concluded that there are certain hue changes when lighting condition is altered. All these work has undoubtedly confirmed the effect of colour appearance change, however, there was no quantitative results available for developing mathematical models for predicting room colours, and most importantly, the results seem to be inconsistent from different studies.

This study takes one step further to accumulate appropriate colour appearance data for room colours and model the colour appearance change between room size colour and small size colour in a real room condition. That is, when a small size colour is chosen with its known CIE *XYZ* tristimulus values, a method can be used to predict its corresponding colour appearance attributes for the same colour in a real room condition.

METHODOLOGY

To investigate the colour appearance change between a small size colour and its corresponding room-size colour, it is necessary to obtain the colour appearance attributes of both colours. The colour appearance attributes of a small size colour can be calculated by applying CIECAM02 to its CIE *XYZ* tristimulus values, which can be easily obtained by direct measurement. However, due to the two problems explained in the earlier section, the colour appearance attributes of a room-size colour cannot be directly calculated using CIECAM02. Therefore, psychophysical experiments were carried out to match the colour appearance of room-size colours by using a small size colour patches. A dedicated experimental room was painted 12 times with a range of selected colours, and psychophysical experiments were carried out to assess colour appearance of one side of the walls under two different illuminants. The colour specification of walls, ceiling, and floor of the experimental room are given below (see section Experimental Design). By analyzing the visual assessment data obtained, size effect and the overall illuminant in the room were mathematically modeled to fit the experimental results. Based on the model developed for size effect and overall illuminant, a method for predicting colour appearance of room colours was developed.

Size effect was studied by investigating the change of colour appearance when the same colour was presented with two different sizes, that is, room size and 10° viewing size under the same illuminant. The colour appearance of the 10° sample can be measured in terms of CIECAM02 colour appearance attributes. To obtain the colour appearance of the real room, a colour matching experiment was performed to visually match the room colour using another 10° size colour patch under a viewing cabinet or a display. The colour appearance of matched colour can again be measured in terms of CIECAM02 attributes. Therefore, the colour appearance change between two sets of measurements should represent the colour appearance changes between the small size and the room size colours.

For a real room, the overall illuminant presented is a combination of the light directly from the light source and the reflected light from the walls. It is of primary importance for the colour appearance of room size colours. Therefore, when the walls were painted in different colours, the overall illuminant in terms of both luminance level and chromaticity varies according to the wall colour. The effect of luminance change can be compensated by a normalization process carried out for each colour. However, the change of chromaticity is critical for colour appearance prediction for both chroma and hue attributes. To investigate the change in illuminant chromaticity under various wall colours, a white diffuser plate having a reflectance of 97% was placed in the room and measured by a Minolta CS1000 tele-spectroradiometer using 0/45 measurement geometry. The chromaticity coordinates were analyzed and their changes under various wall colours were investigated. Note that the Minolta CS1000 tele-spectroradiometer was used to measure all colours in this study and is referred to TSR throughout the article.

EXPERIMENTAL DESIGN

An experimental room with a physical size of 4 m (length) $\times$ 3 m (width) $\times$ 3 m (height) was illuminated under two different light sources: a CIE illuminant D65 simulator having a correlated colour temperature of 6427 K with chromaticity coordinates of $x = 0.3143$ and $y = 0.3312$ and a Cool White Fluorescent lamp representing a typical office lighting, with a correlated colour temperature of 3820 K with chromaticity coordinates of $x = 0.3922$ and $y = 0.3833$. These are referred as D65 and CWF, respectively, throughout the article. The ceiling was painted with a white colour and the carpet was of a mid-gray colour. All four walls were painted with the same colour by a single professional decorator. Initially, a matte white colour using a solvent-based alkyd paint was painted. The room light source measured under this white

TABLE I. Colour appearance attributes for selected colour samples for room painting.

Sample	J	a_c	b_c	Sample	J	a_c	b_c
1	71.2	16.7	−27.8	7	50.9	−13.4	20.3
2	69.0	23.4	16.7	8	10.2	−2.4	2.3
3	84.9	8.6	−6.0	9	80.0	18.3	20.4
4	92.5	2.6	13.3	10	90.6	0.9	25.0
5	50.8	−5.5	−22.1	11	50.9	−29.3	−10.8
6	71.3	−9.5	−26.1	12	92.4	2.3	2.1

colour was adopted as the reference white for calculating the colour appearance in CIELAB or CIECAM02. Twelve test colours selected from the popular range of the ICI Paints gave a reasonable coverage of colour space. They were also measured using a GretagMacbeth (now XRite) CE-7000 spectrophotometer under D65/10° condition and their CIECAM02 colour appearance attributes (J, a_c, and b_c) are given in Table I and also plotted in Fig. 1. Note that the parameters for CIECAM02 were $L_W = 100$, $Y_h = 20$ and average surround. a_c and b_c are defined by CIECAM02 attributes C and h as given in the following equations.

$$a_c = C\cos(h); \quad b_c = C\sin(h)$$

Experimental setup is illustrated in Figs. 2(a) and 2(b). One side of the walls in the room was taken as the target colour to be visually matched by observers. It was first divided into 48 sub-blocks (8 by 6) as shown in Fig. 2(a), each having an equal length and height. Each sub-block center was then measured by the TSR in terms of absolute tristimulus values in cd/m^2 unit. From these measurement data, it was found that lightness values varied due to uneven illumination mainly caused by the position of the light source. White and shaded bars on the ceiling in Fig. 2(a), represent the positions of the D65 and CWF light sources, respectively. Because the two light sources were located at different positions, light distribution of the target wall was affected differently under each light source. Figures 3(a) and 3(b) were drawn to represent the lightness distribution for the two sources, respectively. It can be seen that the lightness of the wall was un-uniformly distributed, where center of the wall is much lighter than either the top or the bottom part of wall. To assess a relative uniform colour patch, the wall was further divided into four and three large regions for D65 and CWF sources, respectively, as shown in black block in Figs. 3(a) and 3(b), respectively. Note that each region consists of a number of sub-blocks. The average measurement for the sub-blocks within a region represents the colour of the region. It was found that the mean colour difference between each sub-block within a region and the average of the region was about 3 CIELAB units. Each colour of a region was assessed using an asymmetric matching technique with two different media: CRT colour and NCS patches, which are named as CRT and NCS experiments, respectively, hereafter (see below).

Ten normal colour vision observers, aged from 20 to 40, took part in experiment and all of them passed the Ishihara vision test. In each observing session, each observer was asked to sit in a fixed position, 1.5 m away from the target wall and between the viewing cabinet and

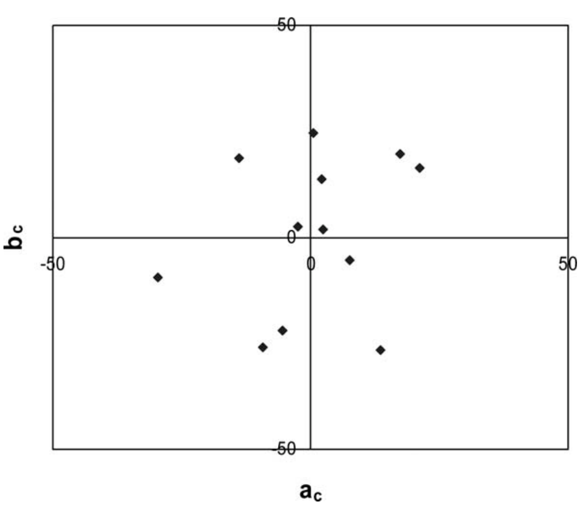


FIG. 1. The selected wall colours plotted in CIECAM02 a_c and b_c diagram.

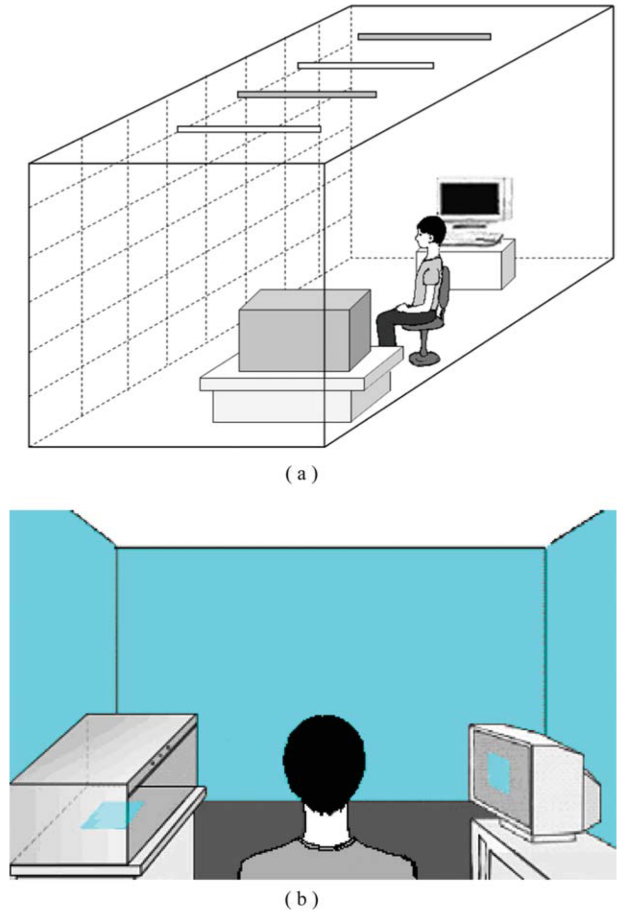
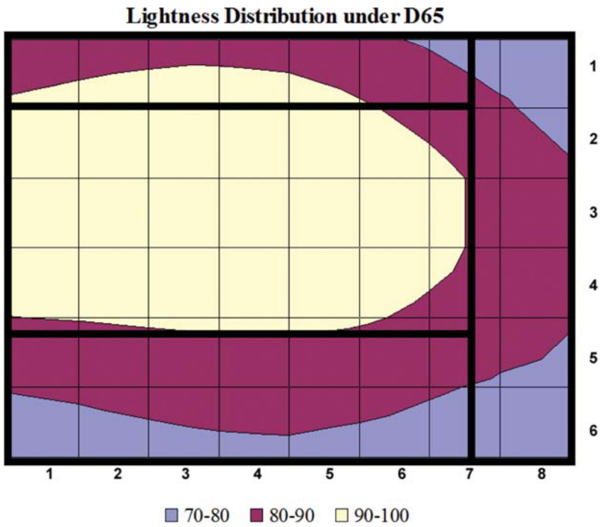
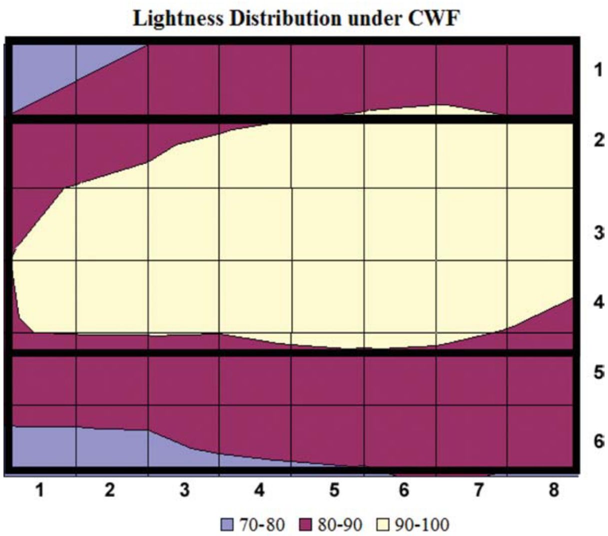


FIG. 2. The experimental set-up for appearance matching (a) experimental room, (b) colour assessment. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]



(a)



(b)

FIG. 3. Light distribution of wall colour under D65 (a) and CWF (b) light sources, where each figure is divided into 48 sub-blocks corresponding to the equivalent position on the wall. Each sub-block in the figure is represented by three lightness ranges: 90–100, 80–90 and 70–80, which are colour-coded corresponding to yellow, red and blue, respectively. For example, if a certain area in the figure appears a yellow colour, it means that the lightness in that particular area on the wall is in the range of 90 to 100. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

the CRT. The ceiling lamps were not visible to the observers during the experiment. The task is to assess and match three or four colour regions on the wall randomly using CRT colours and NCS colour patches under two light sources (D65 and CWF). Note that the CRT and NCS experiments were conducted in separate session. The D65 and CWF lamps used in both viewing cabinet and room were the same. When the light source was changed during the matching session, each observer was asked to view the wall for 3 min to achieve a more completed adaptation to the new lighting condition.

For the CRT experiment, observers were asked to match the colour appearance of the target room size colour by adjusting a colour patch that was displayed on a properly calibrated CRT monitor. The interface was designed to enable observer to change the lightness, chroma and hue separately and continuously for each attribute for the proposed colour patch. The observers were allowed to look back and forth several times and there is no time limit for matching. The monitor was positioned as shown in Fig. 2(a) and characterized using a simple gain-offset-gamma (GOG) model[15,16] with the white point adjusted close match to D65 or CWF, respectively, according to the light source used in the room. Surrounded by black background, the colour patch displayed on the monitor was 8 cm $\times$ 8 cm subtended a viewing angle of about 10°. The black background was chosen because this would make colours displayed on the monitor to be brighter than against a gray background, which enhanced the perceived gamut. During the experiment, all observers could not match a black wall colour for the CRT matching. Most of observers matched the other colours. However, one or two observers could not match very few colours. They felt that the lightness of these wall colours could not be matched using the available monitor colours. They were instructed to choose the maximum lightness which is located in the boundary of the monitor gamut. Overall, these exceptions did not affect the general pattern of the data. Hence, only results for the black wall colour were excluded.

For the NCS experiment, each observer was asked to select a small chip (size 1.2 cm $\times$ 1.8 cm) from an NCS Colour Atlas in a VeriVide viewing cabinet to give a satisfactory match of colour appearance to the target room size colour. The observers were allowed to look back and forth several times and there is no time limit for matching. In each hue page of NCS Atlas, only one chip can be seen and the others were masked by a gray card during each colour matching. The gray card has the similar luminance to the wall of viewing cabinet. Observers moved around the gray mask to search for a colour to match the test colour. In some cases, no colour in the Atlas could produce a satisfactory match to the target colour. To this end, observers were first asked to select a pair of colours, which were closest to the target colour, and then gave each a weight to represent the closeness to the target colour. For example, the weights of two colours could be 20 and 80%.

Colour Appearance Assessment

The method for specifying colour appearance was based on CIE tristimulus values and colour appearance attributes. In this study, the TSR was used for obtaining CIE tristimulus values under the D65 and CWF light sources and CIE 1964 standard colorimetric observer in a real room condition. CIECAM02 model was then used to describe colour appearance for colours having a 10° viewing size.

For the experiment of matching room size colour appearance, each small size colour matched in either CRT or NCS experiment was measured by the TSR in the same position and geometry as it was assessed by human observers. As mentioned in the earlier section, when a target colour was matched by the percentage combination of two colour patches in the NCS experiment, both colours were measured and the final results in terms of *XYZ* values were calculated by using the weights given by the observers.

CIECAM02 was then used to transform CIE tristimulus values to human perceptual attributes: lightness (*J*), chroma (*C*), and hue composition (*H*) for both sizes of colour. Note that lightness defines the amount of light reflected or transmitted from a surface and operates from 0 (black) to 100 (reference white). Chroma defines how chromatic the stimulus is with the zero origin as achromatic colour. Hue composition represents amount of four unitary hues running from 0 (red), 100 (yellow), 200 (green), 300 (blue), and 400 (back to red).[12,17] To use colour appearance model CIECAM02, parameters, such as, the tristimulus values of the reference white (X_W, Y_W, Z_W), the luminance of the reference white (L_W), the surround and the relative luminance factor of background (Y_b) for either CRT or viewing cabinet, were needed as input data for calculating colour appearance attributes for both small size and room size colours. All the parameters used in CIECAM02 for predicting the colour appearance of the room and the small size colours are listed in Table II. Note that two different set viewing parameters were adopted for room colour prediction due to different viewing conditions applied for the CRT and the NCS experiments.

Note also that the luminance of the adapting field L_A is defined by

$$L_A = \frac{L_W Y_b}{Y_W}$$

RESULTS AND DISCUSSION

Observer Variation

Observer variation, which indicates the extent to which individual observer agrees with the majority decision of the group, was calculated in CIELAB colour difference unit.[7] For each target colour, each observer's variation (ΔE^*_{ab}) was calculated by the difference between his/her own judgment and the mean of the whole group. The average ΔE^*_{ab} value from the total 10 observers was then calculated to represent the typical observer variation for a particular colour. The mean from all 12 colours was then calculated to represent the overall observer variation.

When comparing the observer variation between the CRT and the NCS experiments, it was found that the results from the CRT experiment (a mean of 9 ΔE^*_{ab} units with a range between 6 and 10) were slightly smaller than that of the NCS experiment (a mean of 11 ΔE^*_{ab} units with a range between 8 and 16). When compared with Kutas *et al.* study,[8,9] their observer variations ranged from 4.5 to 6.1 ΔE^*_{ab} are smaller than those of current study. This could be partially due to more observers were used in this experiment and partially quite different viewing conditions used in two experiments.

TABLE II. Viewing parameters of CIECAM02 for colour assessment.

	X_W	Y_W	Z_W	L_W	Y_b	Surround
Room (CRT)						
D65	90.5	100	114.1	102.9	1.4	Average
CWF	102.4	100	59.7	104.8	1.2	Average
Room (NCS)						
D65	94.7	100	106.8	514.2	20.0	Average
CWF	104.3	100	46.9	927.3	20.0	Average
Small						
D65	94.9	100	107.0	124.4	20.0	Average
CWF	102.3	100	58.5	236.4	20.0	Average

Size Effect

Before the size effect is considered, a note can be made first about the justification for dividing the experimental room wall into three or four regions as shown in Fig. 3. For example, for a greenish yellow colour (sample 7 in Table I), the lightness differences between the center and each of the top, bottom, and right regions [see Fig. 3(a)] are about 20, 14, and 21 CIECAM02 lightness unit, respectively, under CRT experiment. The mean differences for all 12 colours between the center and each of the top, bottom, and right regions are about 11, 6, and 12 CIECAM02 lightness units, respectively. However, there is no much variation between regions for chroma and hue.

As mentioned earlier, CIECAM02 was used to specify colour appearance attributes: lightness, chroma, and hue for both room and 10° viewing sizes. The size effect can be revealed by plotting the CIECAM02 *J*, *C*, and *H* values between the small size and the room size colours as shown in Figs. 4(a)–4(c) for *J*, *C*, and *H*, respectively. Each point in the diagram represents average result of the observers. Thus, each diagram includes 168 colours, that is, 12 (test colours) × 7 (3 and 4 areas under CWF and D65, respectively) × 2 (CRT and NCS) = 168. For each diagram, a 45° line is drawn to illustrate the size effect. If there is no size effect, all points from the two data sets should all lie on the 45° line. The data are plotted using diamond, minus, plus, and triangle symbols for the CRT under D65, NCS under D65, CRT under CWF, and NCS under CWF experiments, respectively. It can be seen that there is little difference for the data obtained between CRT and NCS methods and between D65 and CWF light sources. This indicates that size effect is independent of the light source and the scaling methods used, which was further proved by using the *t*-test. It also suggests that a simple mathematical equation to predict the size effect based on colour appearance data is possible. Therefore, the following analysis was based on a combined data set obtained from all different viewing conditions. The most

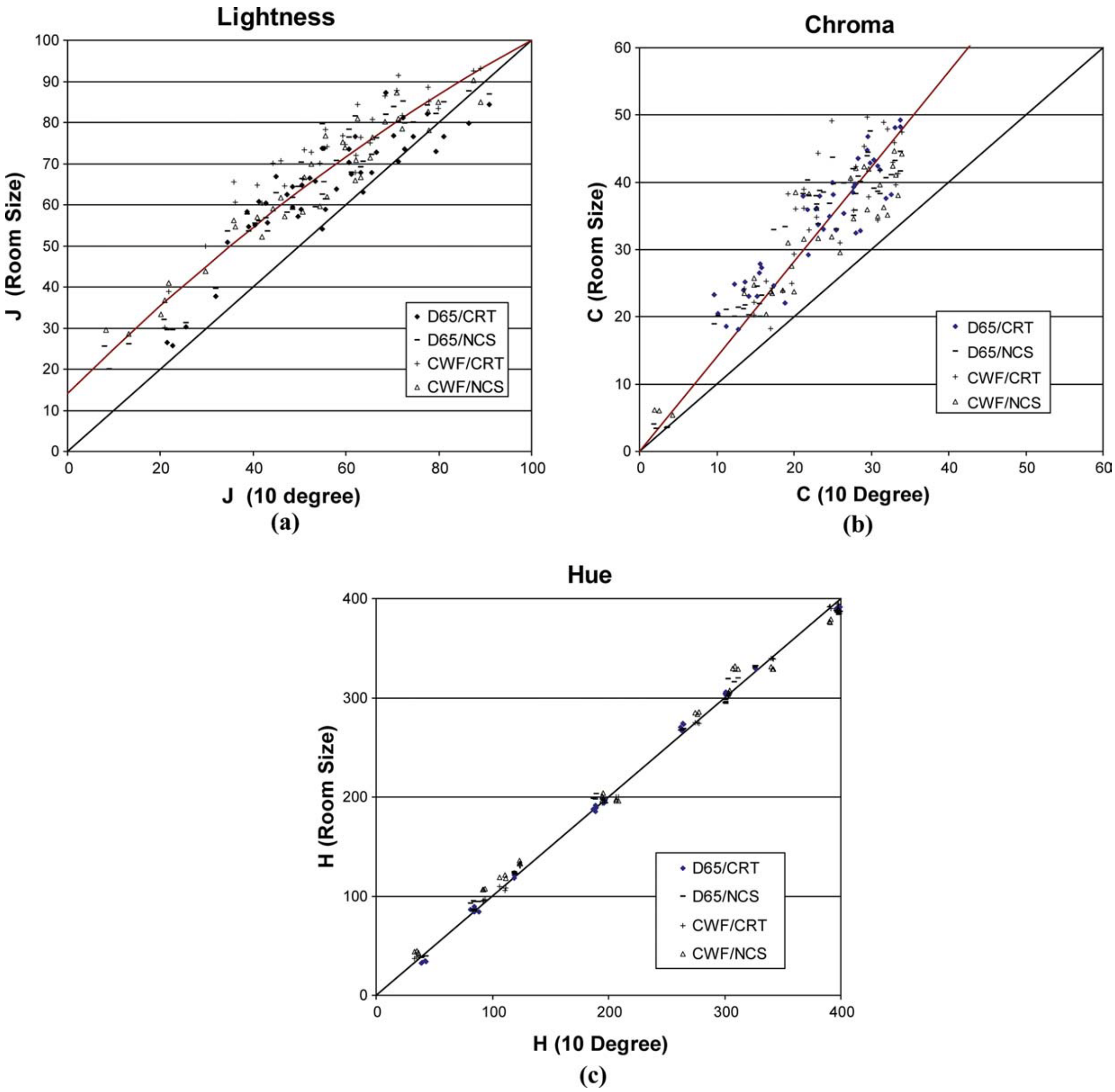


FIG. 4. Relationship between small and room size colours in CIECAM02 (a) lightness, (b) chroma, and (c) hue composition. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

obvious trend in Figs. 4(a) and 4(b) is that most of the points are above the 45° line, which implies that the same colour would appear lighter and more chromatic for room size colours than for small size colour patches. In other words, lightness and chroma increase when the physical size changes from a small patch to room size in a real room viewing condition. However, all points in hue diagram are closely located around the 45° line as shown in Fig. 4(c), which indicates that a change of size has little effect on hue (see Discussion below using Table III). Figure 5 plots the colour shift from the small size colours (lines with full point) to room size colours (lines with open end) in CIECAM02 a_c and b_c diagram. The pattern clearly shows again that room size colours appear to be more colourful with little shift in hue.

The changes of colour appearance between colours in room size and small size were also measured in percentage difference that was represented by coefficient of variation[18] referred as CV as given in Eq. (1) for each perceptual attribute.

$$\mathrm{CV} = (100/\bar{P})\sqrt{\sum_{t=1}^{n}(G_i - P_t)^2/n} \tag{1}$$

TABLE III. Colour appearance difference in CV unit between colours in room and small size.

CV	*J*	*C*	*H*
CRT/D65	17.9	33.8	2.2
CRT/CWF	23.8	35.2	1.8
NCS/D65	19.6	35.6	3.6
NCS/CWF	20.2	29.8	4.9
Overall	20.5	34.0	3.4

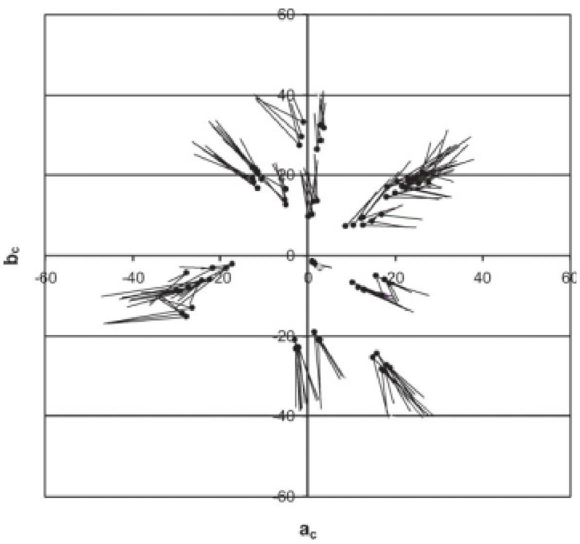


FIG. 5. The colour appearance change in CIECAM02 a_c and b_c diagram. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

where n represents the number of samples in G and P sets, $\overline{P}$ represents the mean value of dataset P. For example, a CV value of 20 means 20% disagreement between the small and the room size's perceptual attributes. While, a CV value of zero means that there is no difference between the small and room size's perceptual attributes. Therefore, the smaller the CV value is, the better the agreement between the two sets of perceptual attributes. Table III lists the CV values for each of the perceptual attributes (J, C, and H). The overall CV values are 21, 34, and 3 for lightness, colourfulness, and hue, respectively. Recall that the typical accuracy performance of CIECAM02[19] using the earlier data sets were 14, 19, and 7 CV values for the lightness, colourfulness, and hue, respectively. The results showed that there is no size effect for hue attributes, but there are large size effects on the lightness and the chroma.

To predict the colour appearance of room size colours, size effect was modeled by fitting a trend line going through the data points in Figs. 4(a) and 4(b). The trend line for each attribute was derived by minimizing the sum of the squares of the differences between the patch and the target wall colours with the following constraints. For lightness, the lightness function was forced to go through the point (100, 100) because lightness is defined to have amount of reflected light against the reference white having a lightness of 100. However, the lightness does not necessary go though (0, 0) point because the lightness perceived for the wall colour illuminated by the ceiling lighting is larger than zero. As for the chroma, the chroma function was also forced to pass the point (0, 0) because colourfulness was defined to have zero for all achromatic colours.

By inspecting the trends in Figs. 4(a) and 4(b), the best-fit curve for lightness should be nonlinear, as chroma can be represented in a linear function. Hence, it was decided to use a quadratic equation to fit the lightness data given in Eq. (2). A liner function was applied for chroma data as listed in Eq. (3). The coefficients for lightness and chroma attributes, α_J, β_J, and k_C, are determined to be -0.0026, 1.19, and 1.41, respectively, through optimization based on the experimental results.

$$J_R = \alpha_J J_S^2 + \beta_J J_S + 100(1 - 100\alpha_J - \beta_J) \tag{2}$$

$$C_R = k_C C_S \tag{3}$$

$$H_R = H_S \tag{4}$$

where J, C, and H stands for lightness, chroma, and hue composition, respectively, and the subscript R stands for room size colour, and S for the small size colour.

The above three equations correlate the colour appearance from small size to room size colours. Figures 6(a)–6(c) show the perceptual attributes of the room size colour against the corresponding predicted results by

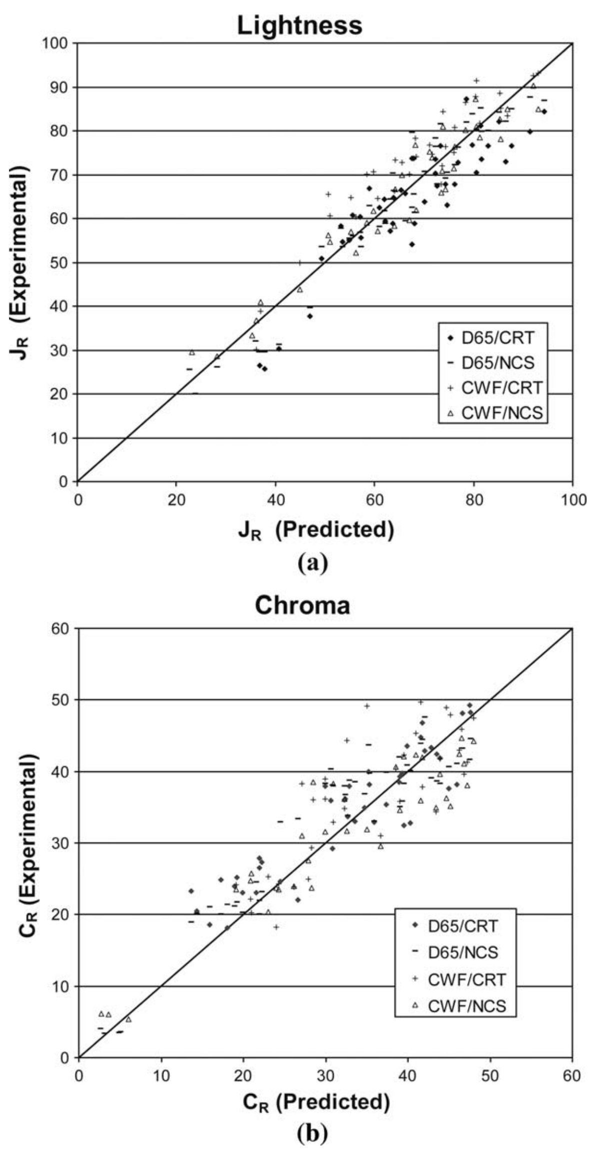


FIG. 6. Relationship between model predicted and experimental results (a) lightness attribute, (b) chroma attribute.

TABLE IV. Model performance in CV unit for size effect correction.

CV	J	C	H
CRT/D65	11.0	12.9	2.2
CRT/CWF	9.3	15.9	1.8
NCS/D65	7.5	13.9	3.6
NCS/CWF	7.2	15.4	4.9
Overall	8.9	14.5	3.4

Eqs. (2)–(4). It can be found that although there are still some scatter between the two data sets, the points are equally scattered on either side of the 45° line. The performances of the mathematical models were also measured by CV values listed in Table IV to represent the percentage difference between the visual results and the predictions of Eqs. (2)–(4) for each perceptual attribute. When comparing the results listed in Tables III and IV, it clearly shows that the size effect correction defined by Eqs. (2)–(4) works well. The lightness CV value reduces from 20.5 (without correction) to 8.9, and the chroma CV value reduces from 34.0 (without correction) to 14.5. The results in Table IV are encouraging. All the CV values are less than the corresponding CV values of the CIECAM02 performance,[19] 14, 19, and 7 CV units for lightness, colourfulness, and hue, respectively.

Illuminant Prediction

The illuminant is of primary importance for colour appearance assessment. In CIECAM02, it is represented as an adopted white to provide a reference stimulus for each particular viewing condition. For a real room, the overall illuminant is a combination of the light directly from the light source and the reflected light from the walls. When the walls were painted in different colours, the overall illuminant varied according to the wall colour. Therefore, to investigate the change in illuminant chromaticity under different wall colours, a white diffuser plate having a reflectance of 97% was placed on the floor right below the light source and measured by the TSR. When plot these chromaticity coordinates, it was found that there are large variation for each light source. This implies that the coloured wall did change the overall illuminant in a room. The colour differences between the colour of white diffuser plate in white wall condition and other coloured wall conditions were calculated. The average colour difference is 9.4 and 8.4 ΔE^*_{ab} for D65 and CWF, respectively. Therefore, the illuminant in a room condition cannot be represented by the colour of light source only.

However, for practical applications it is unrealistic to measure the chromaticity of the overall illuminant under a given wall colour. A model was developed for predicting the chromaticity of overall illuminant in different wall colours by using the colour of light source and wall colour as shown in Eqs. (5)–(7).

$$X_n = f\,X_W + (1-f)X \quad (5)$$

$$Y_n = f\,Y_W + (1-f)Y \quad (6)$$

$$Z_n = f\,Z_W + (1-f)Z \quad (7)$$

where X_W, Y_W, and Z_W are the tristimulus values of the light source that was obtained by the measurement when the wall was painted with white. X, Y, and Z represent the tristimulus values of the painted colour and were calculated using weighting table method recommended by Li *et al*.[20] In fact, the concept was based on our earlier work[21] in associated with CIE TC8-04 for dealing with mixed illuminant condition involving two light sources. The spectral power distribution of the light source was measured when the wall was painted with white, and the spectral reflectance functions of the wall colours were measured by a GretagMacbeth CE7000 spectrophotometer. X_n, Y_n, and Z_n are the tristimulus values of the predicted reference white under any given wall colour, and they needed to be normalized so that Y_n value became 100.

The f value in Eqs. (5)–(7) is the parameter which was derived by minimizing the colour difference between the prediction by Eqs. (5)–(7) and the instrument measurement results. It was found that the best results were achieved at f value of 0.7 which is the same value for both D65 and CWF illuminants, which may imply that the overall illuminant consisted of 70% contribution from the light source and 30% from the reflected light. The fact that f remained almost as a constant under two different illuminants meant that f might be independent of light source. The average optimized result between measurement and prediction is 3 ΔE^*_{ab}, which is much better than the original 8.9 ΔE^*_{ab} when illuminant correction was discounted. Note that, the factor f may depend on the room size and the illumination geometry.

Method for Colour Appearance Prediction for Room Colours

According to the above discussions, a method for reproducing room colours is proposed and shown in Fig. 7 for predicting the appearance of room colours. The method consists of four stages. The first stage is to perform the illuminant correction. The input values are the tristimulus

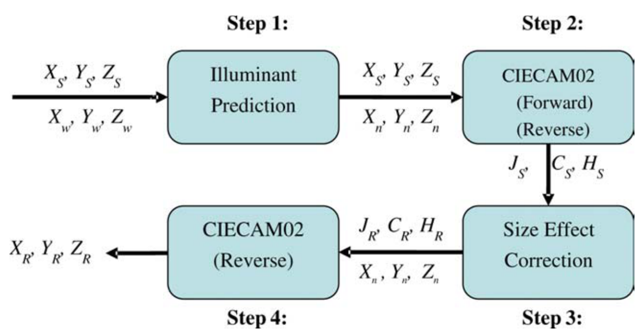


FIG. 7. Block diagram for room colour reproduction. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE V. The performance of the present method in CV units for colour reproduction from small size to room size.

CV	J	C	H
CRT/D65	11	11.3	2.4
CRT/CWF	9.3	15.1	2.9
NCS/D65	7.5	13.3	3.4
NCS/CWF	7.2	14.7	3.6
Overall	8.9	13.6	3.1

values of the small size colour: X_S, Y_S, Z_S and the tristimulus values of the light source: X_W, Y_W, Z_W. Based on these two sets of tristimulus values, the tristimulus values of the mixed illuminant: X_n, Y_n, and Z_n can be computed using Eqs. (5)–(7). Note that in this case, the X, Y, and Z in Eqs. (5)–(7) were replaced by X_S, Y_S, and Z_S. In the second stage, with X_S, Y_S, Z_S, X_n, Y_n, Z_n, and other parameters (e.g., background colour, luminance level, surrounding, as shown in Table II) as required by CIECAM02 as input values, the perceptual attributes J_S, C_S, and H_S of the small size colour can be predicted using the forward model of CIECAM02. In stage 3, the size effect correction [Eqs. (2)–(4)] is applied and the perceptual attributes J_R, C_R, and H_R of the room-size colour can be predicted. The final stage involves the calculation of the tristimulus values of the room-size colour: X_R, Y_R, and Z_R using the reverse model of CIECAM02. Note that the parameters for the reverse CIECAM02 are also given in Table II.

The performance of the above procedure can be evaluated using our experimental data. With tristimulus values of the 12 small size colours as the input values, the perceptual attributes of lightness, chroma, and hue composition for room-size colours can be generated using the above method for room colour reproduction. The procedure performance was measured by CV values as the percentage difference between the predicted results and the results obtained by observer visual assessment for room colours for each perceptual attribute. All results are listed in Table V. When comparing the size effect correction results in Table V with the results without size effect correction in Table III, it is clear that significant improvement has been achieved. When comparing the results in Tables IV and V, it can be found that there is no change in lightness, but for chroma and hue, the results in Table V are slightly better, which is the gain from illumination correction. Besides, the CV values in Table V are also smaller than the corresponding CV values of the CIECAM02.[19]

Discussion

Our major conclusion in this study is that colour would appear lighter and more colourful with little hue change when a small size colour is applied to a real room. The experimental results agree with Billger's studies[10,11] on that room colour appears more colourful. However, there is also a conflict between the results on lightness change. It was found here an increase of lightness, but Billger reported that room colour increases in blackness (an NCS attribute) or darker for room colours. This contradiction may partly due to the different colour appearance attributes used in the two studies (lightness vs. blackness). In this study, lightness and chroma are used and they are two independent attributes. However, in NCS attribute, blackness is a function of both chroma and lightness. Hence, it is possible that when chroma increases more than lightness does, which is the case here, the total visual appearance of the colour appears to have a higher blackness (NCS terminology). Another difference is that in Billger's study, a number of colours were simultaneously assessed in a real room, that is, various colours were painted on different areas of the same wall. However, in this study, there was only one colour painted in the four walls in the room.

When comparing this results with those by Kutas *et al.*,[8,9] this results agreed with their results that there is a lightness increase for larger size stimuli. However, they did not find an increase of colourfulness for larger stimuli. Their results showed only little differences in colourfulness and hue between two sizes.

The above comparisons revealed that different experiments led to different conclusions. This indicates that the colour size effect is very much dependent on the experimental conditions used. However, this results were based on two independent matching methods (CRT and NCS) carried out in a dedicated real room pained with four walls. The results prove to be robust and should be at least applicable for paint in interior application.

CONCLUSIONS

In this article, the size effect of colour appearance between small and room sizes was revealed and modeled. The psychophysical methods for assessing colour appearance on room-size colours were proposed. The walls in an experimental room were painted by 12 different colours and were assessed using two different matching media: CRT and NCS colour atlas under D65 and CWF light sources. During the experiment, to match colour appearance, human observers have to link each room colour to its corresponding small size colour using different media. Substantial colour measurements were made to obtain 10° tristimulus values for wall colours, CRT colours and NCS colour samples. CIECAM02 was used in transforming *XYZ* tristimulus values to human perceptual attributes: lightness, chroma, and hue. The relationship of colour appearance between room and small size colours was investigated. It was found that the size change of a small patch to room size has a large effect on lightness and chroma attributes, but little effect on the hue attribute. The experimental data obtained shows a clear trend that a colour becomes lighter and more colourful when physical size is increased in a room condition. It is also found that these effects are independent of the light source used. For modeling the effect, size effect correction was developed to transform colour appearance from one colour size to another. The overall illuminant in a real room condition was also investigated. The results showed that the wall colour had a considerable effect on the overall illuminant in a room. A mathematical model of illuminant prediction was then developed to predict the overall illuminant for the room based on the given light source and wall colour. Finally, a method for predicting colour appearance of room colours was then derived by combining the illuminant prediction, colour appearance model (CIECAM02) and size effect correction. The performance of this method was evaluated and shown to be effective based on our experimental results.

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1. Fairchild MD, Johnson GM. Color appearance reproduction: Visual data and predictive modelling. Color Res Appl 1999;24:121–131.
2. Fairchild MD. Color Appearance Models, 2nd edition. Reading: John Wiley; 2005.
3. CIECAM02.CIE 159:2004. A color appearance model for color management systems. Vienna, Austria: Commission Internationale de L'Éclairage; 2004.
4. CIE 131:1998. The CIE 1997 interim color appearance model (simple version) CIECAM97s. Vienna, Austria: Commission Internationale de L'Éclairage; 1998.
5. Li CJ, Luo MR, Hunt RWG. A revision of CIECAM97s model. Color Res Appl 2000;24:260–266.
6. Fairchild MD. A revision of CIECAM97s for practical applications. Color Res Appl 2001;26:418–427.
7. Publication CIE 15:2004. Colorimetry, 3rd edition. ISBN 3–901-906–33-9. Vienna, Austria: Commission Internationale de L'Éclairage; 2004.
8. Kutas G, Gocza K, Bodrogi P, Schanda J. Color size effect. In: Proceedings of 10th Congress of the International Color Association, Spain, 2005. p 887–890.
9. Kutas G, Bodrogi P. Color appearance of a large homogenous visual field. Color Res Appl 2008;33:45–54.
10. Billger M. Evaluation of color reference box as an aid for identification color appearance in rooms. Color Res Appl 2000;25:214–225.
11. Billger M. Color in enclosed space—observation of color phenomena and development of methods for identification of color appearance in rooms, PhD Thesis. Chalmers University of Technology, 1999.
12. Luo MR, Clarke AA, Rhodes PA, Schappo A, Scrivener SAR, Tait CJ. Quantifying color appearance. I. LUTCHI color appearance data. Color Res Appl 1991;16:166–180.
13. Stahre B, Harleman M, Billger M. Color emotions in larger and smaller scale. In: Proceedings of AIC 2004 Color and Paints, Porto Alegre, Brazil, 2004. p 27–30.
14. Harleman M. Color appearance in interior daylight: Observations of hue shifts in different compass orientations. In: Proceedings of 9th Congress International Color Association, Rochester, New York, USA, 2001. p 68–71.
15. Berns RS, Motta RJ, Gorzynski ME. CRT colorimetry. I. Theory and practice. Color Res Appl 1993;18:299–314.
16. Berns RS, Gorzynski ME, Motta RJ. CRT colorimetry. II. Metrology. Color Res Appl 1993;18:315–325.
17. Luo MR, Clarke AA, Rhodes PA, Schappo A, Scrivener SAR, Tait CJ. Quantifying color appearance. II. Testing color models' performance using LUTCHI color appearance data. Color Res Appl 1991;16:181–197.
18. Luo MR, Hunt RWG. Testing color appearance model using corresponding color and magnitude estimation data-sets. Color Res Appl 1998;23:147–158.
19. Li CJ, Luo MR, Hunt RWG, Moroney N, Fairchild MD, Newman T. The performance of CIECAM02. In: Proceedings of 10th Color Imaging Conference. Scottsdale, AZ, USA: IS&T/SID; 2002. p 28–32.
20. Li CJ, Luo MR, Rigg B. A new method for computing optimum weights for calculating CIE tristimulus values. Color Res Appl 2004;29:91–103.
21. Sueeprasan S, Luo MR. Incomplete adaptation under mixed illumination. In: Proceedings of 9th Color Imaging Conference. Scottsdale, AZ, USA: IS&T/SID; 2001. p 316–320.