# Colour Appearance Shifts in Two Different-Sized Viewing Conditions

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Received 18 October 2008; revised 16 April 2009; accepted 10 May 2009

*Abstract: This study assessed the effect of size on colour appearance, using a colour matching paradigm where two sizes were presented in a setting similar to a normal colour selection interface. Twelve colours sampling the entire range of the colour spectrum were chosen as target stimuli. The target stimuli consisted of either a large (30° by 50°) or a small (0.5° by 0.5°) test field displayed on a cathode ray tube (CRT). In the experiment, a set of small colour samples consisting of the target and its neighboring colours was presented on the screen. Fifty-seven participants were asked to pick a colour from the sample set that appeared to exactly match the target. Results in CIECAM02 showed a consistent increase in the apparent brightness (Q) but some decrease in saturation (s) for the larger field. Hue shifts were observed to form a systematic pattern. We noticed a discernable trend showing that, for targets of bluish or purplish colour hues, the accuracy of colour matching is lower and colour difference is greater in the condition of the large viewing field.* © 2010 Wiley Periodicals, Inc. Col Res Appl, 35, 352–360, 2010; Published online 17 June 2010 in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.20580

*Key words: color appearance; CIECAM02; color difference; large viewing field*

## INTRODUCTION

The size of the stimulus is known to be a critical factor affecting our ability to judge its colour. The so-called 'colour size effect' is partially because of the physiological properties of the retina. The optical and neural properties of human eyes are optimized around the fovea. As retinal eccentricity increases, several factors affect the quality of the perceived image, such as the distribution of macular pigments, changing rod and cone densities, and receptive field sizes.[1] The photon-capturing efficiency of the outer segments of photoreceptors also varies. In other words, the available resources per unit area for processing small or large-field colour stimuli are very different. There is evidence showing a reduction in saturation under parafoveal viewing conditions.[2–5] Certain shades of red and green have been found to shift toward yellow as the colour stimulus moves from the central to the peripheral field.[5] Because of these eccentricity-dependent factors, an increase in the viewing field size may produce significant changes in perception of colour appearance.

CIE has developed two different standard observers, CIE 1931 and CIE 1964, to describe normal colour vision for 2° and 10° viewing conditions. However, the scale of the representative viewing fields in these well-established standards is far less than that used in current display media; this fact is applicable even to typical PC monitors in everyday use. Hence, size-related colour shifts are not just a phenomenon observed in laboratories. Individual computer users are also aware of this factor when encountering various colour selection interfaces. Some studies have focused on the factors that influence the performance of colour selection, such as the colour models used for arranging colours, or the style of interface design.[6,7] However, the size of samples presented in a colour selection interface has not been examined previously. There are several types of colour selection interfaces: one type displays a set of selected colour samples; another type provides slider tools corresponding to the attributes of the adopted colour models.[7] In fact, the size of colour presented in a palette or in the feedback window of a full colour model interface usually needs to be set smaller than a one-degree visual angle; otherwise the number of colour samples that could be displayed would be quite limited. However, earlier studies[8,9] have found that the colour appearance of a very small colour sample is diffi-

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Contract grant sponsor: National Science Council of Taiwan; contract grant number: NSC 94-2413-H-009-002.

cult to appraise. The actual size of colour samples given by colour selection interfaces of common PC software is in fact quite small. The size of the colour sample provided by the widely used Microsoft operating system is 16 × 11 pixels; in the MS-Office package, it is 11 × 11 pixels. Software specialized for image editing or graphic design, such as Adobe Photoshop™ and Adobe Illustrator™, also present colour samples (referred to as a 'colour swatch' in the Adobe interface) of 11 × 11 pixels. From a typical viewing distance of 60 cm, the colour samples in most colour selection interfaces are probably around, or even under, a $0.5^\circ \times 0.5^\circ$ visual angle. Small size does not just make a colour look indeterminate, as indicated in previous studies,[2,3,8,9] but also creates a perceptual colour discrepancy between the small sample and the large field of the target colour. Frequent colour selection interface users in our institute, such as industrial or visual designers, or image editors, report that they often feel frustrated when a carefully chosen colour from the colour selection interface looks completely different when applied to an object or used in another setting. Therefore, this study proposed to address this problem by assessing the nature and magnitude of size-induced colour changes in a user-friendly PC colour selection interface.

The impact of the effect of size on perceived colour appearance has recently been investigated with a variety of methods.[10–14] colour matching functions derived with monochromatic stimuli suggest that, under a large-field condition, viewers were less sensitive to shorter wavelengths.[15] Other studies, using multiwavelength light or paint as stimuli, have consistently found that apparent brightness increases with the size of the viewing field.[10–14] However, the effect of size on saturation and hue remains unclear. Apparent saturation was found to increase with size in some studies.[11,13] However, a landmark study using an immersed viewing field, equal-luminance background and short stimulus exposure time did not find a systematic relationship between stimulus size and the direction of saturation shifts.[10] Some studies claimed that the enlargement of the viewing field barely influenced hue perception[13]; in contrast, shifts in hue were claimed to be observed in another study.[10] The debate among researchers regarding the effect of size could be attributed to their different experimental techniques. Because the perception of colour appearance is highly context-dependent, we could expect viewing condition variables, such as ambient lighting, stimulus types, exposure times, colour matching procedures, and display media, to directly affect the measured results of any study. In cross-sized colour matching experiments, different display media were often used to acquire larger viewing fields for testing. However, an annoying experimental problem with cross-media colour matching is that even under a well-controlled viewing environment, there is a slight yet discernable colour difference when the same colour is presented on different media.[16] Thus, the comparability of results obtained from different display media is always questionable. Furthermore, considering the methodological rationale, the same-size condition is a necessary control to serve as a reference point for interpreting the colour shifts associated with larger viewing fields. However, most previous studies did not use the same-size viewing condition as a control.

In this study, a cross-size colour matching paradigm was adopted with the following features. First, we used a simplified colour selection interface, similar to that found in real life, on the assumption that a complex interface of colours to match would be quite confusing for untrained observers. In the experiment, the participants were asked to carry out a simple, one-step colour selection task. They found the simplified interface easy to understand and operate. Second, the two stimuli to be matched were shown simultaneously on the same display screen throughout the experiment. There was no cross-media matching in this study. Third, a same-size control condition was introduced to establish the performance baseline against which the magnitude of all size-induced colour shifts could be evaluated.

## METHOD

### Colour Matching Experiment

Figure 1 shows the layout of the experimental interface. The colour to be matched is called the target stimulus; during the experiment it was shown on the upper part of the screen, with the set of related colour samples appearing on the lower part. The target stimulus was displayed either in a larger size or in the same size as the colour samples beneath it. The colour sample sets always contained one true (i.e., colorimetric) match of the target stimulus. The remainder of the small samples consisted of neighboring colours to the true match. Participants were asked to pick the sample that appeared to them to match the target. As the field target size had two levels, and we adopted two groups of colour sample sets, there were therefore four colour matching conditions in total.

### Stimuli

Colours for the target stimuli were selected from the HSV (Hue-Saturation-Value) colour space.[17] The description of colour in terms of hue, saturation, and brightness has been proven to be the most user-friendly format when selecting colour samples.[6] For the purposes of our current study, there are good reasons to specify stimuli from HSV. First, because HSV space is a device-dependent colour space widely used in computer graphic applications, the results can be applied by colour interface designers directly. Most importantly, the inter-colour distances are adequately preserved when transforming HSV values to coordinates of photometric-based colour spaces (see Fig. 2).

Table I shows the detailed specification of target stimuli, and Fig. 2 shows the stimulus distribution. Twelve to-be-matched target stimuli used in the experiment were sampled from the HSV hue circle, from $15^\circ$ to $345^\circ$ with

FIG. 1. Layout of the experimental interface. The upper portion of the screen shows the target stimulus (of two possible sizes) with a set of colour samples shown on the lower portion. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

even intervals of 30°. All targets were set at the same value of 70% saturation and 75% brightness as defined in HSV. They appear nicely spaced within the display media gamut as shown in the CIE1931 $x$–$y$ diagram (Fig. 2, left). The general topology of the target colour distribution is also well preserved when converted into CIECAM02[18] format (Fig. 2, right). The target colours cover the major hue categories across the visible spectrum.

Two groups of colour sample sets were assembled. Each group contained 12 colour sample sets, each of which was compiled around one target colour. The first group (called HB condition) contained colour samples arranged along hue and brightness axes, while samples in the second group (called HS condition) were arranged for hue and saturation. Each colour sample set consisted of seven by five colour samples (35 in total) of which only one was identical to the corresponding target. The irregular polygons in the right two diagrams in Fig. 2 show the range of colour sample sets surrounding each target. The target's location was set as close as possible to the center of the range of the colour sample set so that there is enough headroom in all colour change directions. However, the exact location of each target in a set was varied randomly to prevent the participants from responding blindly to the same location. In each colour sample set, the step size of hue gradient was 5° in terms of HSV colour space. In the HB colour sample sets, the brightness value gradient was 85, 80, 75, 70, and 65%. In the HS colour sample sets, the saturation gradient was 80, 75, 70, 65, and 60%. Taken as a whole, the colour samples represented the full hue circle within the specified brightness and saturation ranges.

The size of target colours was of two possible values, namely 0.5° × 0.5° and 55° (horizontal) × 35° (vertical) visual angle. The actual sizes on the cathode ray tube (CRT) screen were 0.33 × 0.33 cm and 39.6 × 24 cm, respectively. Each small colour sample was 0.5° × 0.5° in size, they were separated from each other by an interval of 0.5° in both vertical and horizontal directions. The size of the interval was set to minimize any potential contextual effect. The background was set at the lowest luminance level of the CRT screen, namely black.

## Participants

Fifty-seven observers, who had all passed the Ishihara colour vision test, participated in the experiment. All were students of Chiao-Tung University, and their participation satisfied a course requirement. There were 41 females and 16 males, aged between 21 and 28 years. Participants

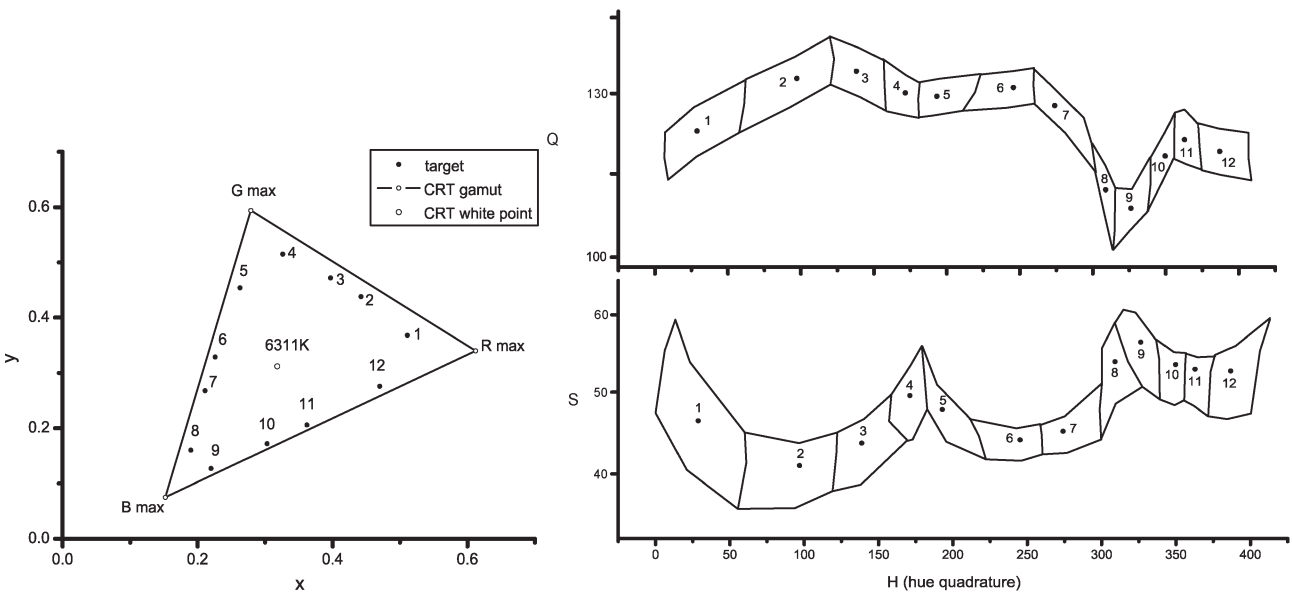


FIG. 2. Stimuli plotted in x–y chromaticity diagram (left) and in CIECAM02 (right). The white point of the display CRT is 6311K (127 cd/m$^2$, $x = 0.318$, $y = 0.312$). The stimuli were evenly distributed in the available colour gamut (R: 38.1 cd/m$^2$, $x = 0.612$, $y = 0.34$; G: 77 cd/m$^2$, $x = 0.279$, $y = 0.594$; B: 12.7 cd/m$^2$, $x = 0.152$, $y = 0.075$). The two diagrams (right) show the twelve target stimuli in H–Q (brightness against hue quadrature) and H–S (saturation against hue quadrature). The irregular, connected polygon enclosing the target point represents the variation range of neighboring colour samples.

TABLE I. The number specification and coordinates in HSV, CIELAB and CIECAM02 of target stimuli.

| Target | H-S-V | L* | a* | b* | *Q* | *s* | *H* | Colour name |
|---|---|---|---|---|---|---|---|---|
| 1 | 15-70-75 | 66.06 | 47.64 | 46.56 | 131.76 | 44.02 | 28.66 | reddish orange |
| 2 | 45-70-75 | 81.68 | 8.49 | 62.09 | 144.97 | 38.75 | 97.83 | yellow |
| 3 | 75-70-75 | 85.05 | −17.39 | 63.76 | 147.07 | 41.6 | 139.47 | greenish yellow |
| 4 | 105-70-75 | 78.93 | −51.85 | 56.14 | 140.41 | 47.99 | 170.94 | yellowish green |
| 5 | 135-70-75 | 78.81 | −62.18 | 27.73 | 139.88 | 50.14 | 175.95 | green |
| 6 | 165-70-75 | 81.18 | −42.97 | −12.56 | 141.91 | 42.59 | 243.65 | green-blue |
| 7 | 195-70-75 | 75.64 | −24.03 | −33.68 | 136.65 | 43.72 | 275.88 | blue |
| 8 | 225-70-75 | 54.34 | 23.36 | −66.83 | 116.24 | 52.21 | 308.59 | deep blue |
| 9 | 255-70-75 | 48.13 | 61.23 | −74.94 | 111.21 | 54.82 | 326.81 | purple-blue |
| 10 | 285-70-75 | 60.52 | 75.32 | −54.09 | 126.01 | 51.58 | 349.55 | Purple |
| 11 | 315-70-75 | 63.99 | 78.39 | −33.68 | 130.17 | 50.84 | 362.94 | purple-red |
| 12 | 345-70-75 | 60.78 | 71.01 | 7.22 | 127.43 | 50.82 | 386.59 | Purplish pink |

were not aware of the purpose or methodology of the project.

## Apparatus

A gamma-corrected 21-inch CRT (EIZO Flex Scan T965) with regulated power supply was used for stimuli display. The actual CRT display size was 40 × 29.8 cm. Resolution setting was 1600 dots by 1200 lines at 104 Hz. The peak white and colour gamut of the CRT is represented in Fig. 2 (left). A uniformity check was done by dividing the CRT into 8 × 6 regions, and the output of each region was measured with a well-calibrated Photo-Research™ PR-650 SpectraScan spectroradiometer. The mean output intensity was 127 cd/m$^2$, with a maximum value of 129.3 cd/m$^2$ (+1.81%) measured in the central zone and a minimum value of 123.8 cd/m$^2$ (−2.52%) at the lower-left corner of the monitor. The measuring distance was 355 mm and sample size was 10 × 10 cm (over the whole field of the lens). The measuring geometry recommended by PhotoResearch was followed. The adopted value for a standard observer was CIE1931.

The experiment was conducted in a darkened room; the only light came from the CRT. The viewing distance from the screen was 38 cm and was kept constant by a chin rest. Participants used a keyboard to key in the number of the matching colour. The flow of the experiment was controlled with Presentation® (Neurobehavioral System). The Colour Engineering Toolbox for Matlab[19] was used for converting results into CIECAM02[18] and calculating the colour difference data.

## Procedure

Every participant was asked to perform 96 forced-choice colour matching trials (12 target colours, two groups of colour sample sets, namely HB and HS conditions, two size conditions, and two trials per condition). The stimulus layout is shown in Fig. 1. Participants were instructed to choose one colour out of the colour sample set that looked ‘identical or most similar’ to the target colour, then key in the number of that colour sample. As the position of the true match was varied between trials, and the order of trials was randomized, there should not

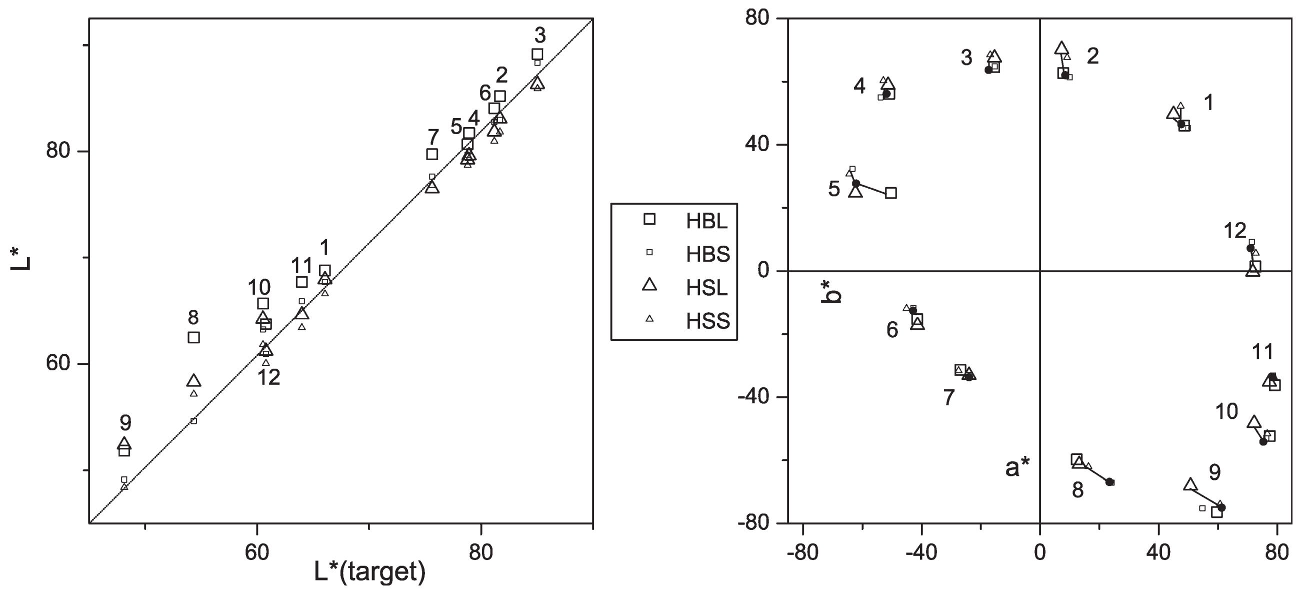


FIG. 3. Comparison of results of different conditions in L*a*b*. The left diagram shows L* of target against mean measured L* under four conditions. The right diagram shows the plot of mean results in an a* against b* format.

TABLE II. List of mean results in L*a*b*, colour differences (CIE DE2000), and hit rate of responses.

| Target | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HBL | L* | 68.82 | 85.2 | 89.16 | 81.73 | 80.68 | 84.07 | 79.73 | 62.51 | 51.84 | 65.7 | 67.73 | 63.75 |
| | A* | 48.64 | 7.79 | −15.51 | −50.94 | −50.42 | −41.47 | −26.94 | 12.37 | 59.66 | 77.49 | 79.17 | 72.63 |
| | B* | 46.09 | 62.73 | 64.7 | 56.14 | 24.67 | −15.25 | −31.33 | −59.75 | −76.36 | −52.28 | −36.21 | 1.39 |
| | $\Delta E_{00\ M}$ | 2.29 | 2.41 | 2.89 | 1.95 | 3.55 | 2.66 | 3.47 | 8.71 | 3.87 | 4.49 | 3.15 | 3.57 |
| | $\Delta E_{00\ STD}$ | 1.69 | 3.42 | 1.21 | 1.17 | 1.98 | 1.63 | 1.54 | 0.98 | 2.73 | 3.14 | 1.51 | 1.77 |
| | Hit rate | 15.8% | 8.8% | 3.5% | 7% | 12.3% | 5.3% | 4.4% | 0.9% | 6.3% | 3.5% | 5.3% | 7.9% |
| HBS | L* | 67.73 | 82.97 | 88.35 | 80.01 | 79.67 | 82.75 | 77.64 | 54.66 | 49.13 | 63.26 | 65.9 | 60.96 |
| | A* | 49.94 | 9.93 | −15.34 | −53.83 | −63.4 | −42.76 | −24.18 | 24.04 | 54.82 | 76.3 | 78.58 | 71.42 |
| | B* | 45.22 | 61.39 | 64.86 | 55.07 | 32.38 | −11.71 | −32.94 | −67.03 | −75.21 | −52.98 | −33.1 | 9.18 |
| | $\Delta E_{00\ M}$ | 2.03 | 1.32 | 2.49 | 1.15 | 1.81 | 1.17 | 1.47 | 0.47 | 2.9 | 2.42 | 1.59 | 0.86 |
| | $\Delta E_{00\ STD}$ | 2.12 | 2.24 | 1.09 | 2.08 | 2.61 | 1.97 | 1.55 | 1.27 | 2.56 | 3.15 | 2.88 | 1.93 |
| | Hit rate | 23.7% | 13.2% | 14% | 12.3% | 12.3% | 14.9% | 15.8% | 26.3% | 25.4% | 12.3% | 8.8% | 23.7% |
| HSL | L* | 67.95 | 83.07 | 86.31 | 79.61 | 79.21 | 81.84 | 76.5 | 58.32 | 52.4 | 64.24 | 64.64 | 61.22 |
| | A* | 45.01 | 7.29 | −15.38 | −51.32 | −62.35 | −41.39 | −24.01 | 13.18 | 50.75 | 72.25 | 77.35 | 71.76 |
| | B* | 49.67 | 70.25 | 67.62 | 58.91 | 24.71 | −17.22 | −33.02 | −61.22 | −68.07 | −48.18 | −35.16 | −0.253 |
| | $\Delta E_{00\ M}$ | 2.86 | 2.59 | 2.23 | 1.09 | 1.28 | 2.95 | 0.67 | 5.9 | 5.14 | 3.6 | 0.84 | 3.19 |
| | $\Delta E_{00\ STD}$ | 2.07 | 2.13 | 1.99 | 1.1 | 0.65 | 1.64 | 0.49 | 3.41 | 2.67 | 3.44 | 1.78 | 3.83 |
| | Hit rate | 14.9% | 12.3% | 14% | 14.9% | 9.6% | 6.1% | 4.4% | 4.4% | 5.3% | 1.8% | 9.6% | 6.1% |
| HSS | L* | 66.6 | 81.84 | 85.91 | 79.33 | 78.69 | 80.96 | 76.8 | 57.17 | 48.39 | 61.83 | 63.43 | 60.07 |
| | A* | 47.41 | 9.121 | −16.86 | −52.91 | −64.42 | −45.12 | −27.55 | 16.3 | 60.73 | 76.69 | 78.9 | 72.78 |
| | B* | 52.22 | 67.69 | 68.56 | 60.32 | 30.71 | −11.86 | −31.58 | −61.99 | −73.89 | −51.54 | −33.72 | 5.58 |
| | $\Delta E_{00\ M}$ | 2.64 | 1.43 | 1.56 | 1.19 | 1.09 | 0.98 | 2.24 | 3.91 | 0.37 | 1.59 | 0.48 | 1.06 |
| | $\Delta E_{00\ STD}$ | 1.86 | 1.52 | 2.09 | 1.37 | 0.7 | 1.43 | 2.16 | 3.62 | 2.23 | 2.15 | 0.94 | 2.1 |
| | Hit rate | 25.4% | 19.3% | 11.4% | 10.5% | 14% | 14.9% | 17.5% | 31.6% | 29% | 12.3% | 15.8% | 24.6% |

have been any noticeable learning effect. Response time was not limited, when the participant had keyed in each chosen number a new trial was presented. All trials were grouped into four short sections of 24 trials. There was a compulsory break no shorter than one minute between sessions. Participants could also extend the break time if they wished to do so. The average time for completing the entire experiment was about 30 minutes.

## RESULTS AND DISCUSSION

The results are presented and discussed in two parts: (1) General size effect. (2) Colour appearance shifts according to brightness, saturation, and hue in CIECAM02.[18]

### General Size Effects

The general size effects was assessed through the following indexes: the mean subjective matches in CIELAB,[20] mean colour differences between targets and their matches, and the hit rate in each condition. The results of the 12 target colours in four conditions, namely HB of large viewing field (HBL) condition, HB of small viewing field (HBS) condition, HS of large viewing field (HSL) condition, and HS of small viewing field (HSS) condition, are plotted in Fig. 3, in an $a^*$-$b^*$ diagram. The matching results in terms of $a^*$-$b^*$ value were measured with PhotoResearch™ PR-650 SpectraScan spectroradiometer directly. The measuring setting was the same as that described in the Apparatus section. Mean $L^*a^*b^*$ values in each condition are listed in Table II. The colour differences between targets and the subjective matches were calculated by CIE DE2000[21] colour difference formula. The mean colour difference and STD of each target in four conditions are listed in Table II, and denoted with $\Delta E_{00\ M}$ and $\Delta E_{00\ STD}$, respectively. Hit rate data (count of exact matches/total trails), are also summarised in the table.

The overall colour differences found in the large viewing field condition (HBL and HSL) is larger than that in the small conditions (HBL mean = 3.58, STD = 1.77; HBS mean = 1.64, STD = 0.72; HSL mean = 2.7, STD = 1.64; HSS mean = 1.55, STD = 0.99). The mean colour difference between the HBL and HBS and that between HSL and HSS conditions were found to be very significant ($P < 0.01$ in both cases, Student's $t$-test). Figure 4 compares all colour differences in a histogram. It shows that the magnitude of colour differences is highly hue-dependent. The most remarkable size-induced colour shifts are found in target numbers 8 and 9, as they

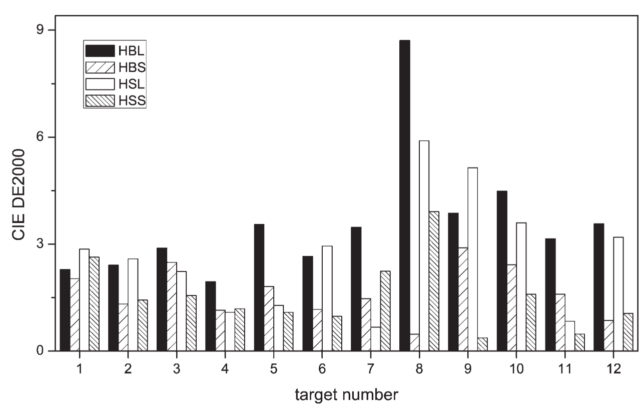


FIG. 4. Comparation of CIE DE2000 colour difference for each condition.

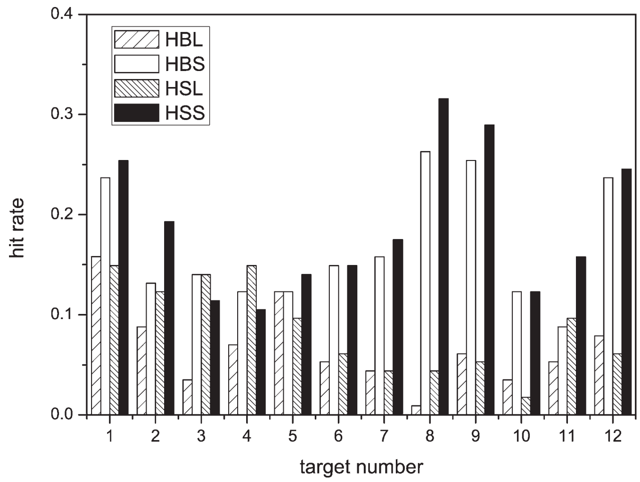


FIG. 5. Comparation of hit rates for all conditions.

produced large colour differences in large conditions but relatively mild differences in small conditions.

The hit rate can be regarded as colour selection accuracy in the experiment, and may provide useful information about selection performance within this type of colour selection interface. The observed hit rates (see histogram in Fig. 5) also vary drastically across different conditions and target colours. Hit rates for the small target size conditions (HBS and HSS) are significantly higher than those for the large target size conditions (HBL and HSL) ($P < 0.01$ in both cases). It has been reported that the colour appearance of a small-size stimulus is hard to identify,[8,9] and our hit rates in the small target size condition, being lower than 25% on average, seem to confirm such an observation. However, it is even more difficult to colour match successfully when the target is large.

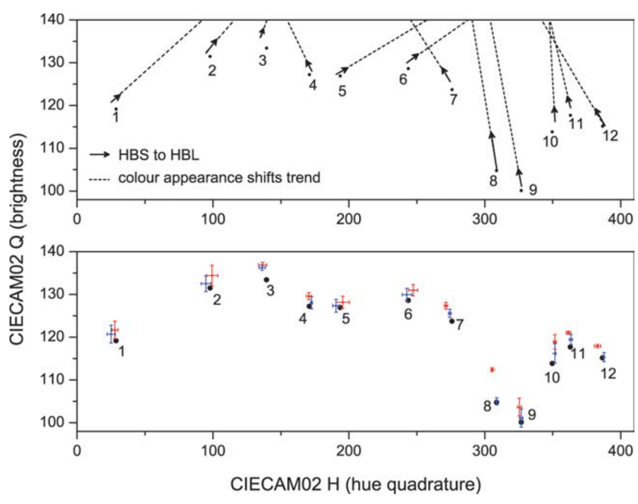


FIG. 6. Results of the HB condition in *Q* (brightness, y axis) against *H* (hue quadrature, x axis) of CIECAM02. Solid black circles with numbers denote the location of target stimuli. The arrows in the upper diagram are vectors projecting from the mean results of HBS to the corresponding mean results of HBL. The dotted lines are auxiliary lines extended from vectors for better visualising the underlying colour shift tendencies. The lower diagram shows the mean results and the targets. Red signs denote mean results of colour selection in large condition (HBL), with error bars that present STDs along x-axis and y-axis respectively. Blue signs denote those for the small condition (HBS).

## Colour Appearance Shifts

To compare the size effect on major attributes of colour appearance in different conditions, the CIE XYZ tristimulus values of colour matching results were measured with PhotoResearch™ PR-650, and converted into values of *Q* (brightness), *s* (saturation), and *H* (hue quadrature) of CIECAM02.[18] The Colour Engineering Toolbox for Matlab[19] was used for converting CIE XYZ into CIECAM02.[18] The inputting parameters for CIECAM02 were set as follows: the adopted white point is the peak white of the CRT: $X_w = 101.57$, $Y_w = 100.00$, $Z_w = 118.11$. $L_A$ was set as 25.4 cd/m$^2$, 20% of the maximum intensity of the CRT. The surround is set as dark.

The statistical summaries of the HB and HS conditions are plotted in Figs. 6 and 7, respectively. Upper diagrams in the two figures show the tendency of colour appearance shifts in a vector format, whereas lower diagrams in both figures show the means along with error bars to represent the participants' responses and to what extent they deviated from the target. Since the small conditions were designed as the same size control group, the vector projecting from one average match in HBS/HSS to the corresponding HBL/HSL data point represents the direction and the magnitude of the average colour shift across these two sizes. The subjective brightness increased in most HBL conditions, whereas the saturation seemed to decrease in HSL conditions.

To take a closer look at the pattern of brightness shifts, we plotted the subjective against the target brightness (*Q*) as shown in Fig. 8. In the HBL condition the perceived brightness was higher than for the HBS condition, espe-

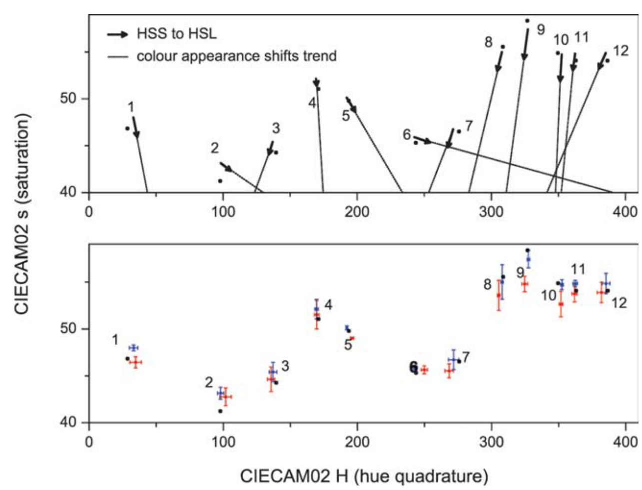


FIG. 7. Results of the HS condition. The representation of signs and formats is the same as for Fig. 6.

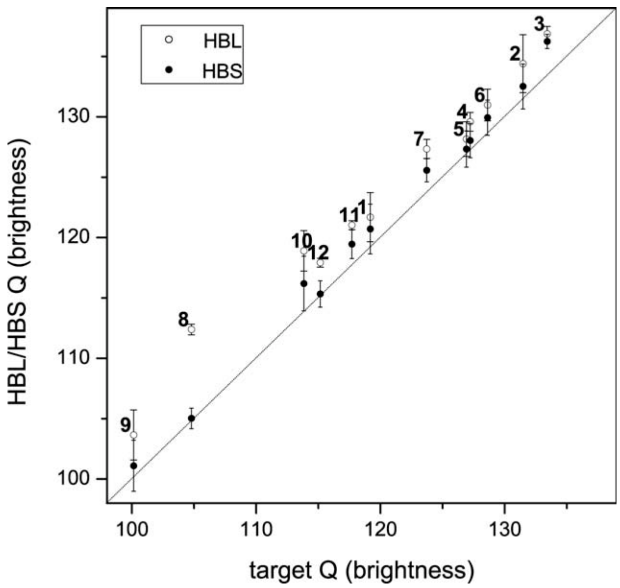


FIG. 8. The measured *Q* of HBL and HBS conditions against the original target *Q*.

cially for target 8. The mean *Q* difference between the 12 target stimuli and their corresponding matches were as follows: for the large size condition (HBL), mean $\Delta Q = 3.39$, STD = 1.62 (max = 7.6 (target 8), min = 1.24 (target 5); for the small size condition (HBS), mean $\Delta Q = 1.27$, STD = 0.83 (max = 2.83 (target 10), min = 0.17 (target no.12). The matches in large size conditions lie above the diagonal line, indicating that they all looked brighter than the original target. Pair-wise comparison of the brightness increase between the two size conditions is statistically significant ($P < 0.01$). The overall subjective brightness of HBL was higher than that of HBS; the overestimation is most pronounced in target 8 (a deep blue). Other neighbouring purplish and bluish targets, e.g., 7, 9, 10, and 11, also produced relatively higher *Q* values.

Notwithstanding diverse measuring methods and viewing environments, previous researchers consistently found an increase in size-induced brightness.[9–13] The finding that larger colour patches look brighter seem to be a reliable colour perception phenomenon, but the magnitude of the brightness increase reported in various studies varies considerably. Human eyes are extremely sensitive to brightness change. Studies involving cross-display media or a colour memory matching method could overestimate the magnitude of apparent brightness change. In the present experiment, the limited brightness range of the colour sample sets could have reduced the magnitude of subjective brightness shift. Therefore, it is possible that the actual effect of size-induced brightness increase would be greater or more evident than what we observed.

The shifts of perceived saturation are more complicated. Figure 9 plots HSL / HSS *s* against target *s* and shows the magnitude of saturation shifts. Most matches of HSL conditions, specifically for green (5), bluish to purplish (7–11), and reddish targets (12 and 1), fall below the diagonal line, indicating that they all look less saturated than the original target. The mean $\Delta\ s$ of HSL/HSS and targets is as follows: in HSL, mean $\Delta\ s = -0.64$, STD = 1.38 (max = 1.53 (target 2), min = $-3.53$ (target 9); in HSS, mean $\Delta\ s = 0.52$, STD = 0.79 (max = 1.91 (target 2), min = $-0.9$ (target 9). Pair-wise comparison of the $\Delta\ s$ between the two size conditions is significant ($P < 0.01$). It also indicates that the perceived saturation for all targets decreases in large viewing conditions when taking HSS as the baseline. The magnitude of *s* decrease is larger in targets 8–10, namely blue to purple hues.

The most interesting and valuable finding of this study relates to the pattern of hue shifts. In vector H–Q, H–S diagrams (Figs. 6 and 7), the dotted lines are auxiliary lines extended from vectors for better visualizing the underlying colour shift tendencies. Some neighbouring vectors, such as those of targets 1–4, 5–9, and 10–12 in the H–Q vector diagram, seems to converge to a common vanishing point (or zone). In the H–Q vector diagram three convergent groups can be identified, namely red-orange to yellow-green tones (1–4), green to purple-blue tones (5–9), and purplish tones (10–12). However, the convergent pattern is less recognizable in the H-S vector diagram. Interestingly, some systematic hue shift has also been previously observed.[10] Specifically, there is a tendency for the reddish test targets to shift toward pink as size increases. The convergent hue shifts noted in this study indicate that some categorical order of hue perception comes into play when performing cross-size colour matching.

To examine the pattern of hue shifts across all conditions, the magnitudes of hue shifts were plotted in the unit of $\Delta H$ (difference in hue quadrature) shown in Fig. 10. The graphs are obtained by substracting the *H* values of the reference (either the target's *H* or the control group HBS/HSS's *H*) from the values of the measured results.

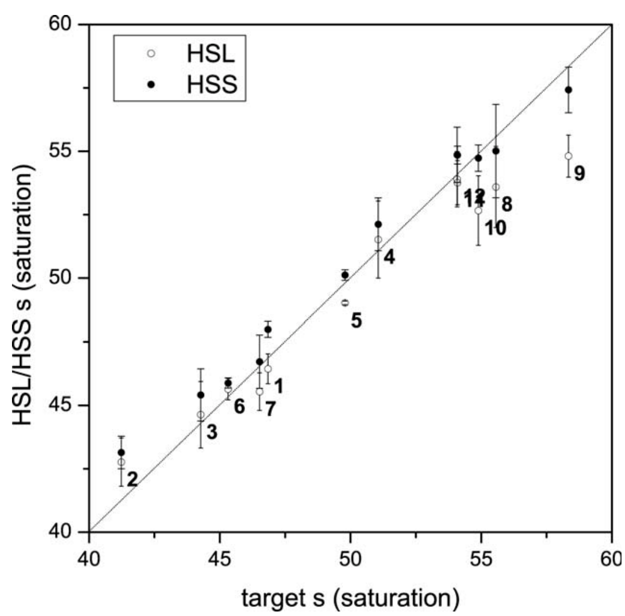


FIG. 9. The measured *s* of HSL and HSS conditions against the original target *s*.

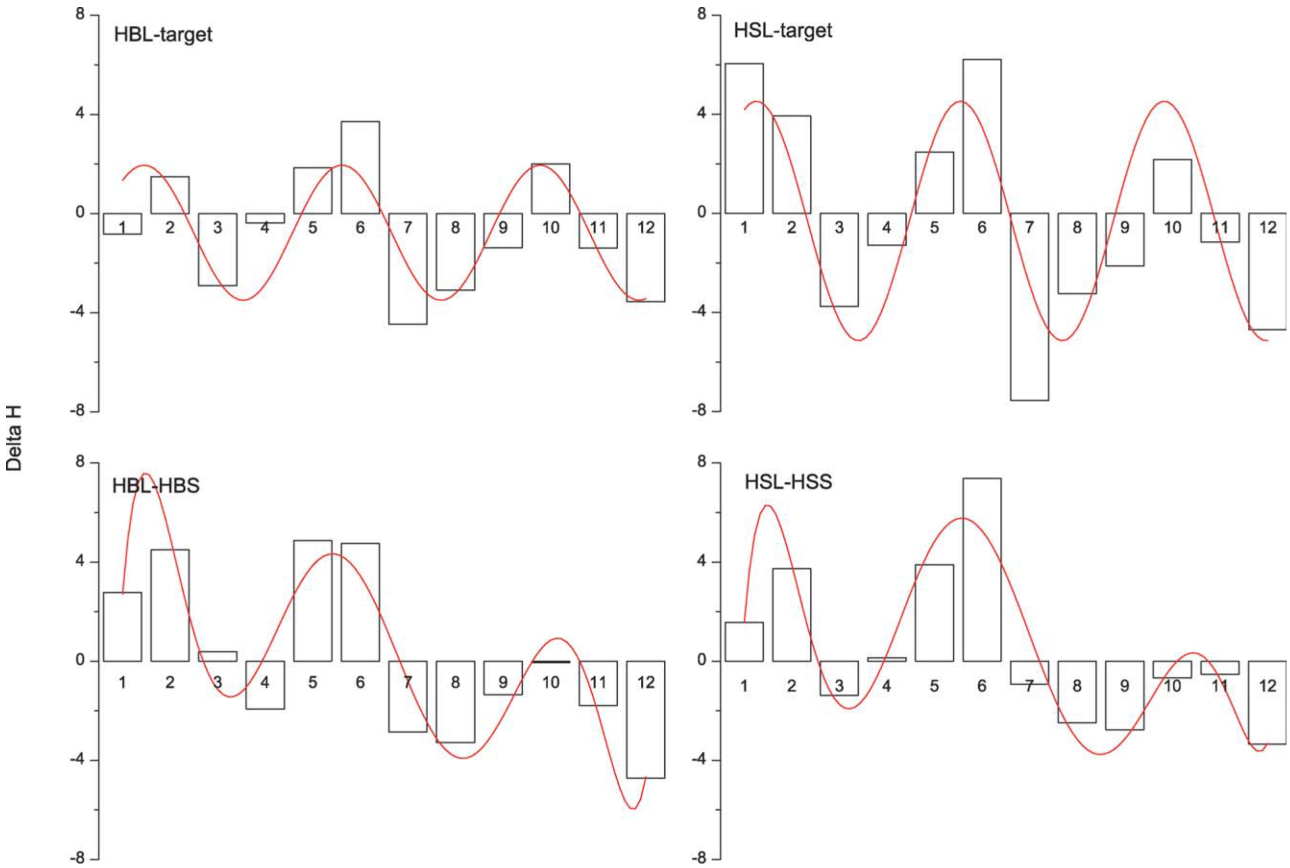


FIG. 10. The modulation pattern of $\Delta H$ using targets (the upper two graphs) and the small conditions (the lower two graphs) as baselines. The x axis is the target number, and the y axis $\Delta H$. The curve in each graph is the nonlinear fitting result. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

To highlight the modulation pattern of hue shifts, a nonlinear curve fitting was carried out with values of $\Delta H$ as input variables. The $\Delta H$ pattern of HBL/HSL against target is relatively simple, and can be captured by a sinusoid fitting, whereas that of HBL/HSL against HBS/HSS requires an eighth-order polynominal curve fitting. The fitting results exhibit a certain regularity of hue shifts in different conditions across the hue circle. In all histograms, the rise and fall of bars alternate in a rhythmic manner, discounting the slight phase shift that occurred when different baselines were used. The zero-crossing points correspond to hues that their neighbouring colours are converging toward.

## CONCLUSIONS

This study examined size-induced colour appearance shifts under viewing conditions similar to a typical experience of using a colour selection interface. The results show a significant brightness increase in large size conditions across target colours, which is consistent with results of previous studies.[10–14] The level of perceived saturation, by contrast, tends to decrease with stimulus size. Although systematic hue shifts have seldom been observed or discussed in previous studies, we found an interesting pattern associated with induced hue shifts by size. In the large size conditions the hues around the hue circle are apparently drawn in groups to some anchoring colours, i.e., a typical representation colour within the hue group. We propose that this phenomenon might be due to some kind of categorical perception of colours,[22] a hypothesis that calls for future studies to verify.

We also noted that the performance of cross-size colour matching is target hue dependent. The greatest size-related effect is found with bluish and purplish hues, where selection accuracy was poor and the colour difference is big. Interestingly, bluish targets appear brighter but less saturated in the large viewing field conditions. Thus, it appears that the brightness gain of bluish colours observed in the large conditions behaves like whiteness instead of from intensity gain of the given colour. The added whiteness in the large field effectively dilutes the purity or saturation of that colour as a result.

Given the hue-dependent nature of size effect, the current colour selection interfaces using colour samples of a uniform size might have room for improvement. As potential users cannot foresee the magnitude of size effect for each sample they select, they can easily become frustrated when a surprisingly great discrepancy occurs. One possible enhancement might be to render the size of colour samples according to their size effect. On one hand, the size of a sample will be informative about the expected size effect. On the other, the size difference between the sample and the applied field would then be reduced to some degree to counteract the size effect. Whether such a nonuniform palette would serve the user better is a question that awaits further empirical assessment.


## ACKNOWLEDGMENTS

The authors thank the anonymous reviewers for their critical comments that have greatly improved this article.



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