Effects of angular distances between colour stimuli on colour conspicuity

Rumiko Takata and Ichiro Katayama*

Graduate School of Art and Design, Joshibi University of Art and Design, Japan
** Faculty of Biology-Oriented Science and Technology, Kindai University, Japan*
**Email: katayama@waka.kindai.ac.jp*

Colour stimuli systematically selected from the HJC colour space of CIECAM02 were juxtaposed at four angular distances (10°, 30°, 60°, and 90°). The observers evaluated the colour conspicuity of the colour stimuli using the paired comparison method. Results showed that the colour conspicuity of chromatic colours at an angular distance of 90° was higher than at angular distances of ≤60° because, at angular distances of 10° to 60°, simultaneous comparisons were made on two presented stimuli in peripheral vision where colour perception declines, whereas temporal comparisons were made in central vision at an angular distance of 90°.

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Introduction

Many studies have been conducted on subjective colour phenomena, such as colour contrast and assimilation that occur when different colours are combined [1-2], and the emotional effects and harmony of colour combination [3-4]. In addition, a quantitative evaluation of colour difference has been actively studied due to its importance in the quality control of various products [5-6]. These studies assume that different colours are adjacent to each other. In everyday life, however, we process information by identifying nonadjacent multiple colour stimuli in various positions within the visual field and directing our attention to them. For example, when driving a vehicle, we must pay attention and respond quickly to colour information, such as traffic signals and road signs [7], of which the positional relationship changes from moment to moment within the visual field [8-9]. Furthermore, unfamiliar streets, large hospitals, airports, and office buildings require signs with appropriate colour conspicuity against environmental colours because difficulty in wayfinding causes psychological and physiological burdens [10-12].

Nowadays, many people own PCs and smartphones, and e-commerce is indispensable to our daily lives. Under such circumstances, they need to find targets from colour stimuli in various positions on the monitor screen, and appropriate colour conspicuity of screen elements [13-14] is required from the viewpoint of usability [15-16]. An example of air traffic control work as a special situation, a complex visual task carrying an extremely heavy cognitive load, indicates that the time for situation awareness by controllers is significantly shortened by adding colours to pieces of information simultaneously displayed on the air traffic control monitor [17-18]. However, how the three attributes of colour stimuli that do not adjoin each other within the visual field and the angular distance between colour stimuli affect colour conspicuity has not yet been revealed. If the colour conspicuity of colour stimuli changes according to the positional relation between them, it will become possible to control information to be highlighted within the visual field not only on the screen but also in real space. Thus, this study conducted visual evaluation experiments to clarify how the angular distance between two colour stimuli affects the colour conspicuity of colour stimuli.

Experiment

Two colour stimuli were presented on the achromatic colour background on a liquid crystal display (LCD), and the observers evaluated their colour conspicuity using the paired comparison method (Ura's paired comparison) [19-20]. Two colour stimuli were presented in a horizontally separated position, and the angular distance between the stimuli was set at four angles.

Experimental setup

The attribute of appearance of colour stimuli was set using hue (*H*), lightness (*J*), and chroma (*C*) of CIECAM02 [21]. The observation parameter of CIECAM02 was set to an average surround (*c*=0.69, *N*c=1.0, *F*=1.0). The screen size of the LCD (TH-65DX950; Panasonic) was 1428 mm in width, 804 mm in height, and 1639 mm in diagonal. With 35% of maximum white luminance, an achromatic colour equivalent to the standard illuminant D65 was presented in full screen as the achromatic colour background equivalent to lightness *J*60. The hues of the presented colour stimuli were set to *H*0, *H*100, *H*200, and *H*300, each corresponding to unique hues of red, yellow, green, and blue, respectively. For these four hues, lightness was set at four levels of *J*20, *J*40, *J*60, and *J*80, with chroma *C*40. However, under the conditions with angular distances between the stimuli set at 30° and 90°, the lightness of each hue was set at three levels of *J*40, *J*60, and *J*80. In addition, the chroma of each hue was set at four levels of *C*20, *C*40, *C*60, and *C*80, with lightness *J*60. However, under the conditions with angular distances between the stimuli set at 30° and 90°, chroma was set at three levels of *C*40, *C*60, and *C*80. In addition to these chromatic colour stimuli, *J*40 and *J*80 achromatic colour stimuli were prepared. Figure 1 shows the distribution of the presented stimuli in the HJC colour space.

The angular distance between two colour stimuli presented on the *J*60 achromatic colour background was horizontally set at 10°, 30°, 60°, and 90°, centred around the gaze target shown in the centre of the screen. For example, when the angular distance was 10°, a pair of different colour stimuli was presented equally on both sides of the gaze target, with each stimulus presented 5° away from the gaze target. The LCD was placed inside a 600-mm-deep observation box whose inside wall was black. Fixing their heads using a jaw stand, the observers observed the colour stimuli at 600 mm from the display with binocular and natural vision through an aperture (250 mm long×200 mm wide; Figure 2). The presented colour stimuli were 3° in diameter, and adjustments were made so that their apparent shape, diameter, and colorimetric value would remain constant, regardless of where they were presented. The observation box was placed inside a darkroom. It was also confirmed that all colour stimuli presented on the achromatic colour background could be perceived in surface colour mode.

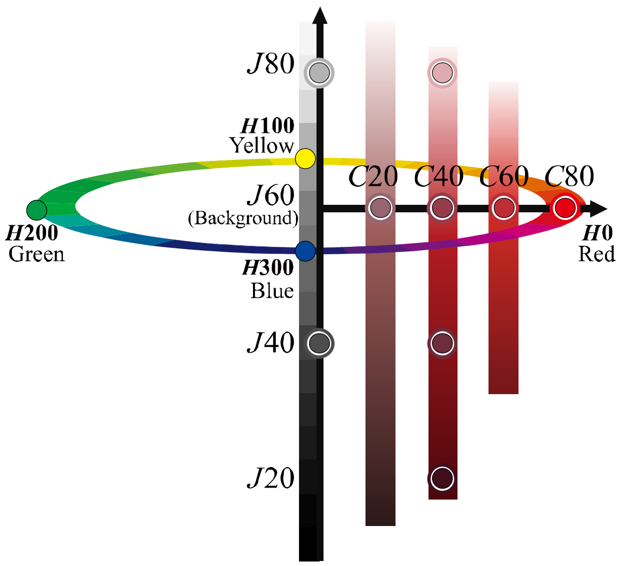

Figure 1: Distribution of the presented stimuli in the HJC colour space (only hue H0 is shown).

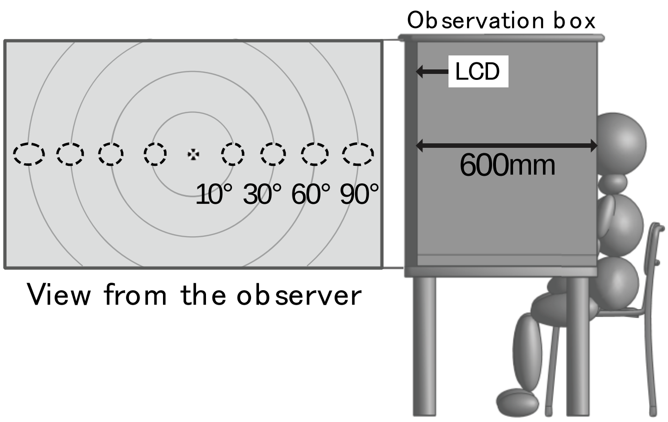

Figure 2: Experimental setup and view from the observer.

Experimental procedure

A 1° diameter ring-shaped gaze target[1] was presented in the centre of the achromatic colour background equivalent to lightness *J*60. After the experimenter verbally informed observers that colour stimuli for evaluation would be presented, the gaze target was erased at the same time as the colour stimuli were presented on both sides of the gaze target. The colour stimuli were presented for 500 ms. The observers evaluated the colour conspicuity of the colour stimuli shown on both sides in five levels: "The left one stands out," "The left one slightly stands out," "Neither one stands out," "The right one slightly stands out," and "The right one stands out," and stated their response verbally. The experimenter recorded their response when only the achromatic colour background equivalent to *J*60 was shown on the LCD. Once the experimenter recorded responses, the gaze target was presented again. The same procedure was repeated thereafter (Figure 3).

[1] The gaze target was consisting of black and white, adjusted so that the average lightness of the black and white was *J*60.

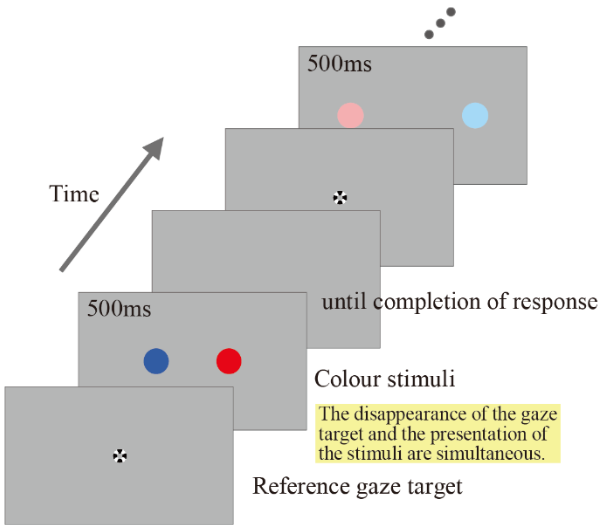

Figure 3: Experimental setup and view from the observer.

The gaze target was given for the observers to observe the colour stimuli on both sides equally, and they were not required to stare at the centre of the background when they evaluated the colour conspicuity of the colour stimuli.

Combination of colour stimuli and angular distance

The experiment was conducted in three parts as follows:

1. Experiment I: Combination of constant lightness, constant chroma, four hues, and four angular distances.

   Six different colour stimuli were used: chromatic colour stimuli in four hues (*H*0, *H*100, *H*200, and *H*300) with lightness *J*60 and chroma *C*80 and two different achromatic colour stimuli (lightness *J*40 and *J*80). The number of combinations of the presented stimuli was as follows: ${}_6C_2$×2 (inversion of right and left positions)×4 angular distances (10°, 30°, 60°, and 90°)=120.

2. Experiment II: Combination of four lightnesses, constant chroma, four hues, and four angular distances.

   The following colour stimuli were used: chromatic colour stimuli in four hues (*H*0, *H*100, *H*200, and *H*300) with constant chroma *C*40 and four levels of lightness (*J*20, *J*40, *J*60, and *J*80) and an achromatic colour with lightness *J*40. However, at angular distances of 30° and 90°, the lightness of chromatic colour stimuli was set at three levels (*J*40, *J*60, and *J*80). Therefore, the number of combinations of the presented stimuli was as follows: 4 (hues)×${}_5C_2$×2 (inversion of right and left positions)×2 angular distances (10° and 60°)+4 (hues)×${}_4C_2$×2 (inversion of right and left positions)×2 angular distances (30° and 90°)=256.

3. Experiment III: Combination of constant lightness, four chromas, four hues, and four angular distances.

   The following colour stimuli were used: chromatic colour stimuli in four hues (*H*0, *H*100, *H*200, and *H*300) with constant lightness *J*60 and four levels of chroma (*C*20, *C*40, *C*60, and *C*80) and an achromatic colour with lightness *J*40. However, at angular distances of 30° and 90°, the chroma of chromatic colour stimuli was set at three levels (C40, C60, and C80). Therefore, the number of combinations of the presented stimuli was as follows: 4 (hues)×$_5C_2$×2 (inversion of right and left positions)×2 angular distances (10° and 60°)+4 (hues)×$_4C_2$×2 (inversion of right and left positions)×2 angular distances (30° and 90°)=256.

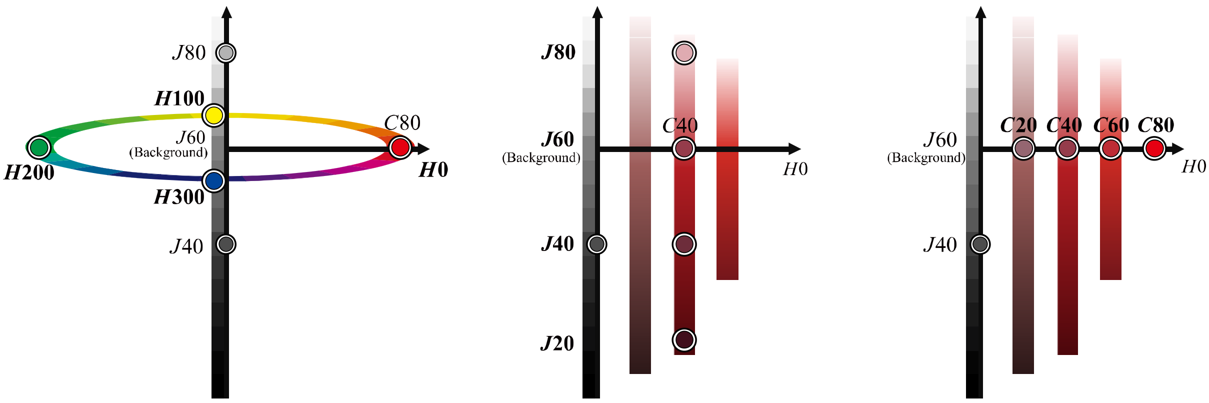

Figure 4: Distributions of the colour stimuli used in Experiments I–III, respectively (from left to right).

In each experiment, the paired colour stimuli were presented in random order among the observers. Figure 4 shows the distribution of the colour stimuli used in each experiment within the HJC colour space (Experiments II and III show hue H0 only).

Observers

The observers were undergraduate and graduate students (9 males and 6 females; mean age, 22.7 years; standard deviation age, 1.0) with normal colour vision and visual acuity (including corrected vision).

Results and discussion

In Experiments I to III, the interval scale of the evaluation results[2] of colour conspicuity for each angular distance was set out. Figure 5 shows the results of Experiment I. To grasp the relative relationship of colour conspicuity for each colour stimulus, the results were normalised by a 1% yardstick, with the colour conspicuity of a J40 achromatic colour stimulus set as 0. In addition, the colour stimuli of the same hue were connected by the polygonal lines. In Figure 5, a scale unit corresponds to a 1% significant difference in colour conspicuity. Figure 5 shows that when lightness and chroma are the same, the colour conspicuity of blue and red stimuli is high and that of yellow stimuli is low regardless of the angular distance. This is considered to be the effect of the difference in brightness between hues due to the Helmholtz-Kohlrausch effect [22].

Figure 6 shows equivalent lightness [23] that considered the Helmholtz-Kohlrausch effect on each colour stimulus used in Experiment I. It is estimated from the equivalent lightness of each colour stimulus that the descending order of perceived brightness is blue (H300), green (H200), red (H0), and yellow (H100).

[2] The conspicuity of a colour stimulus is relative to different colour stimuli determined by the paired comparison method.

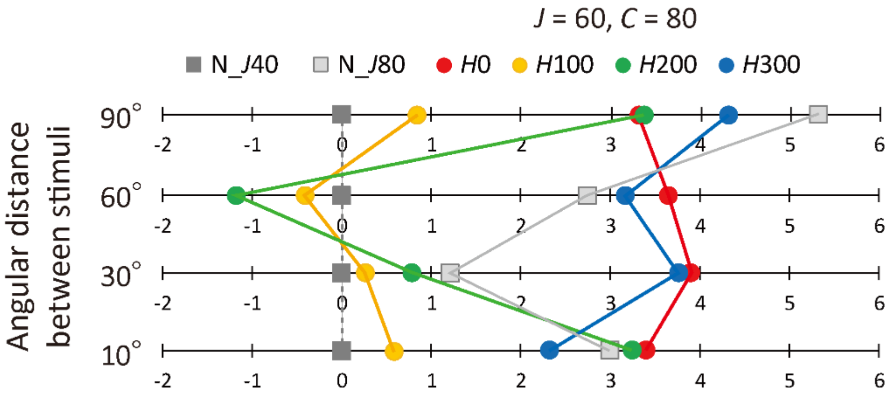

Figure 5: Results of Experiment I.

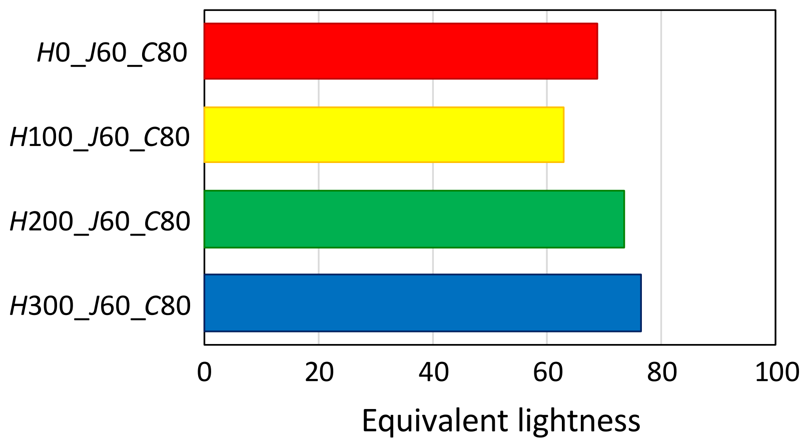

Figure 6: Equivalent lightness of each colour stimulus used in Experiment I.

In Figures 5 and 6, at an angular distance of 90°, there was a tendency for the colour conspicuity of colour stimuli with high equivalent lightness to increase. However, the colour conspicuity of green stimuli changed considerably according to the angular distance; it was at the same level as that of the *J*40 achromatic colour stimulus at an angular distance of 30° and significantly lower than that of the *J*40 achromatic colour stimulus at an angular distance of 60°. In addition, the *J*80 achromatic colour stimulus was low in colour conspicuity at an angular distance of 30° and higher in colour conspicuity than chromatic colour stimuli at an angular distance of 90°. Up to the angular distance of 60°, green-hued stimuli became significantly lower in colour conspicuity as the angular distance increased. This is due to a decline in colour perception in peripheral vision [24-29], but no noticeable decrease in colour conspicuity was observed in colour stimuli other than green-hued ones. In contrast, the colour stimuli, including green-hued ones, were high in colour conspicuity at an angular distance of 90°. This result contradicted the decline in colour perception in peripheral vision.

Next, Figure 7 shows the results of Experiment II. As in Figure 5, the results were normalised by a 1% yardstick, with the colour conspicuity of a *J*40 achromatic colour stimulus set as 0. The evaluation results of colour conspicuity are shown for each angular distance in Figure 7a and each hue in Figure 7b. Colour stimuli of the same lightness were connected by the polygonal lines to grasp the relative relationship of the evaluation results. Overall, Figure 7a shows that, at angular distances of 10° to 60°, the stimuli with a difference in lightness with the background (*J*60 achromatic colour) were high in colour conspicuity. In addition, at an angular distance of 60°, chromatic colour stimuli with lightness *J*20 (×) were at the same level of colour conspicuity as chromatic colour stimuli with lightness *J*80 (●). At angular distances of 10° to 60°, chromatic colour stimuli with the same lightness as the background were equally in colour conspicuity with or significantly lower than *J*40 achromatic colour stimuli. However, at an angular distance of 90°, all chromatic colour stimuli were significantly higher in colour conspicuity than *J*40 achromatic colour stimuli, regardless of lightness. Figure 7b shows that at any angular distance, chromatic colour stimuli with lightness *J*40 and *J*80 were significantly higher in colour conspicuity than *J*40 achromatic colour stimuli, and chromatic colour stimuli with a difference in lightness with the background were high in colour conspicuity, regardless of the angular distance. In Figure 7a and b, *J*60 chromatic colour stimuli connected by the bold lines (▲) are described later.

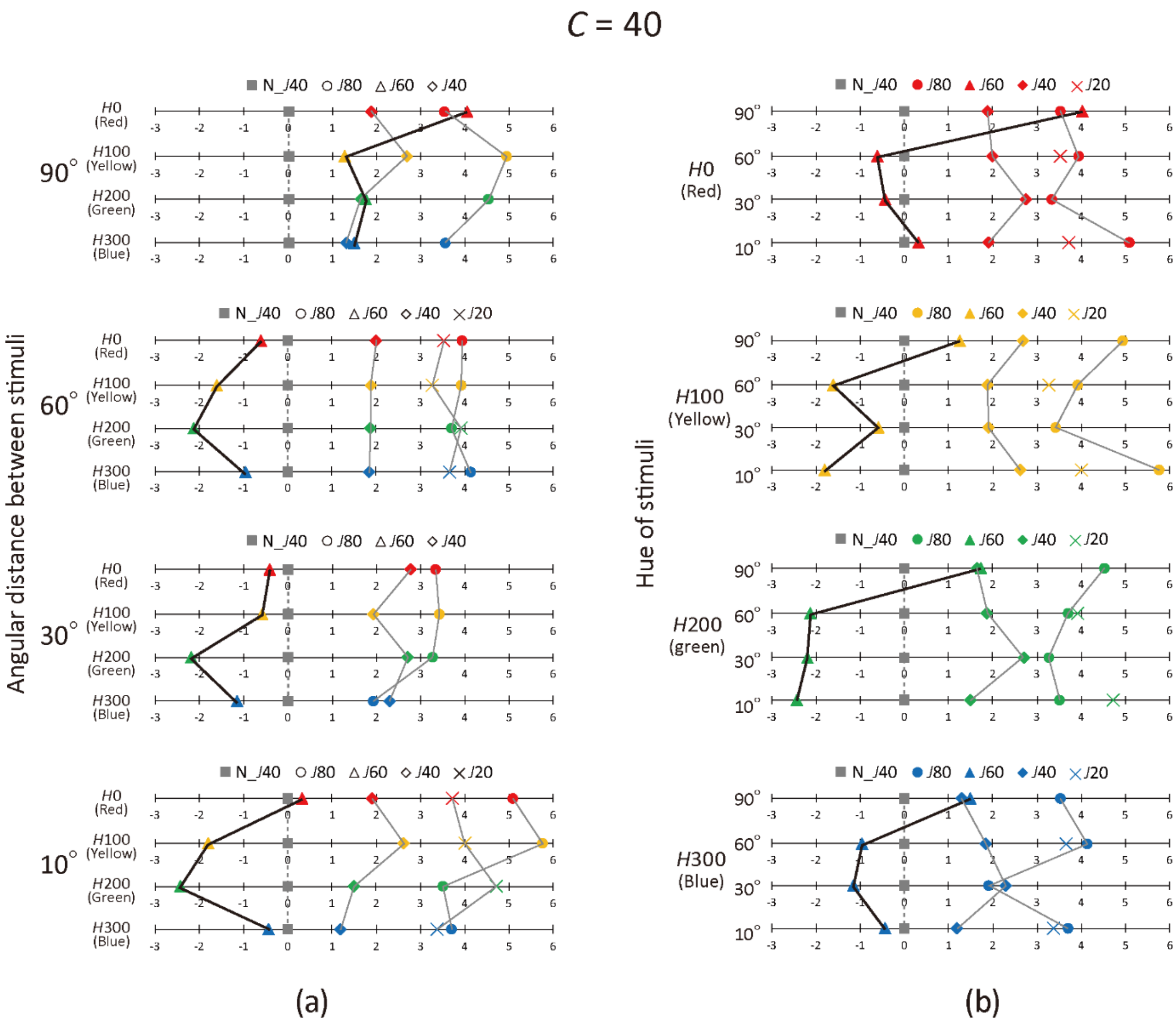

Figure 7: Results of Experiment II.

Figure 8 shows the results of Experiment III. As in Figures 5 and 7, the evaluation results were normalised by a 1% yardstick, with the colour conspicuity of a *J*40 achromatic colour stimulus set as 0. The evaluation results of colour conspicuity are shown for each angular distance in Figure 8a and each hue in Figure 8b. Colour stimuli of the same chroma were connected by the polygonal lines to grasp the relative relationship of the evaluation results. Figure 8a shows that, at angular distances of 10° to 60°, the colour stimuli with a higher chroma were, by and large, high in colour conspicuity and that, at an angular distance of 90°, the colour stimuli in all hues were significantly higher in colour conspicuity than *J*40 achromatic colour stimuli. Overall, Figure 8b suggests that at any angular distance, the stimuli significantly higher in colour conspicuity than *J*40 achromatic colour stimuli were limited to red-hued *C*60 and *C*80 and blue-hued *C*80.

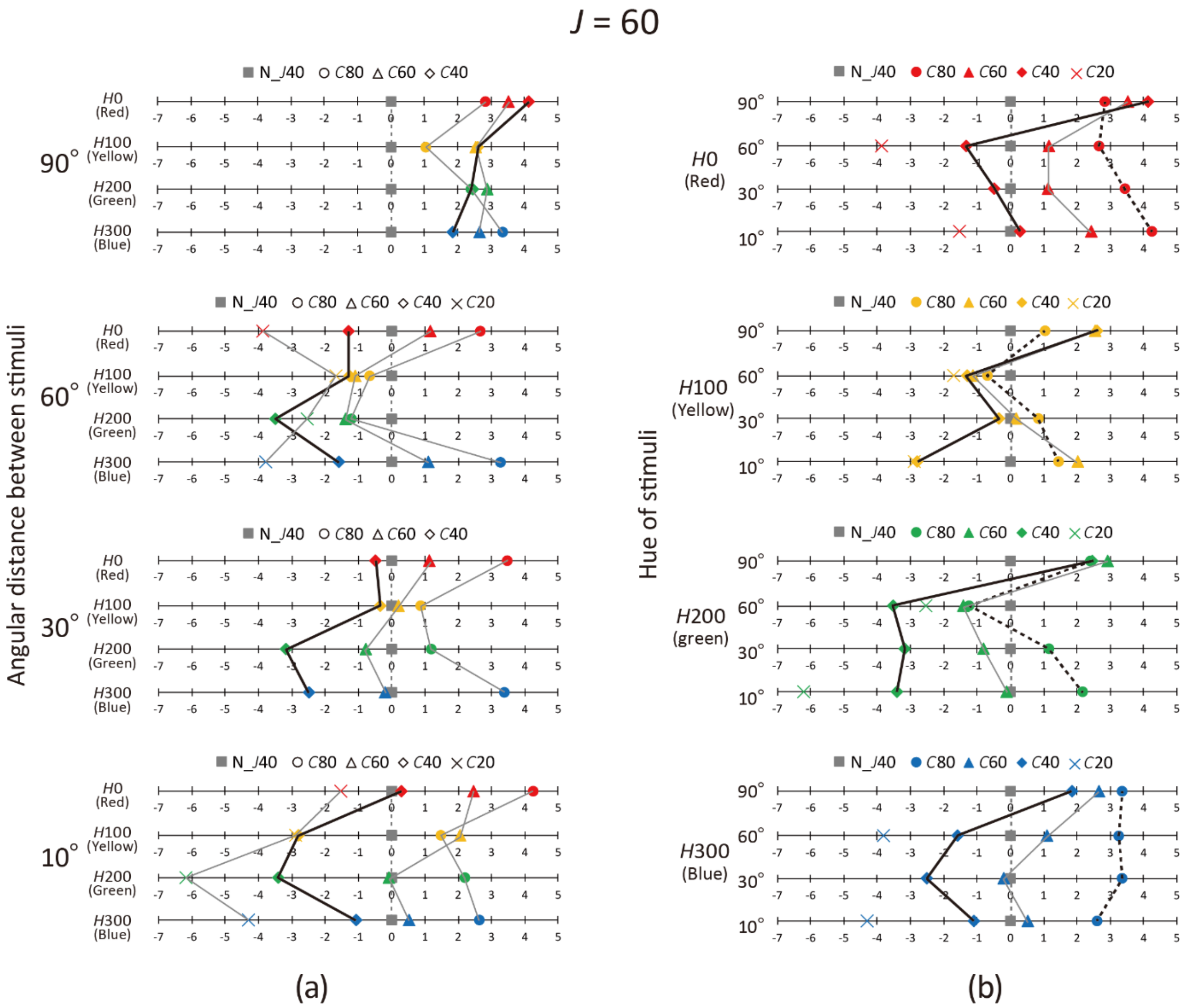

Figure 8: Results of Experiment III.

Figures 7 and 8 show that all stimuli connected by bold lines have lightness *J*60 and chroma *C*40. The shape of the bold lines and the relative positions with respect to *J*40 achromatic colour stimuli are similar between Figures 7 and 8. This suggests the qualitative concordance of the evaluation results of colour conspicuity in Experiments II and III. Furthermore, the colour stimuli connected by dashed lines are identical to that in Experiment I (lightness *J*60 and chroma *C*80). The lines connecting each colour stimulus in Figure 5 are similar in shape to the dashed lines in Figure 8b, and the colour conspicuity relative to *J*40 achromatic colour stimuli is qualitatively in good agreement between Experiments I and III. Based on the above, when focusing on identical colour stimuli between three experiments, the observers consistently evaluated colour conspicuity.

Taken together, the results of the experiments suggested a tendency that the colour conspicuity of chromatic colour stimuli was high at an angular distance of 90° and low at angular distances of 10° to 60°. This results from simultaneous comparisons made in a peripheral vision where colour perception declines [24-29] when colour stimuli were presented at angular distances of 10° to 60°. In contrast, when the angular distance between colour stimuli was 90°, it is considered that simultaneous comparisons in peripheral vision became difficult; instead, temporal comparisons were made in central vision, with the result that the colour conspicuity of chromatic colour stimuli became evident. It is understood that the time required to process the information on stimuli presented within the visual field is ~50 ms for detecting letters and simple stimuli [30] and ~150 ms for detecting targets from complex visual information, such as landscapes [31]. Therefore, 500 ms, the time in which the stimuli were presented in this study, is considered enough to continuously evaluate the colour conspicuity of two colour stimuli. However, because this study did not track the observers' visual line during the experiments, it will be necessary to examine the relationship between the angular distance and the visual line using an eye-tracker to clarify the angular distance between stimuli at which a shift from peripheral vision to central vision is made.

Conclusions

Colour stimuli systematically selected from the HJC colour space of CIECAM02 were juxtaposed at four angular distances (10°, 30°, 60°, and 90°), and the observers evaluated the colour conspicuity of those colour stimuli by the paired comparison method. The following results were obtained at angular distances of 10° to 60°. When the lightness and chroma of colour stimuli were constant, the colour conspicuity of yellow and green stimuli decreased as the angular distance increased. In addition, when the chroma of colour stimuli was constant, the colour conspicuity of colour stimuli with a large difference in lightness with the background was high. When the lightness of colour stimuli was constant, the colour conspicuity of colour stimuli with high chroma was high, and there was a tendency for the colour conspicuity of red and green stimuli to decrease as the angular distance increased. However, the results were substantially different at an angular distance of 90°; the colour conspicuity in all hues was higher than when the angular distance was ≤60°. From the above results, at angular distances of 10° to 60°, simultaneous comparisons were made on two presented stimuli in a peripheral vision where colour perception declines, whereas, at an angular distance of 90°, temporal comparisons were made on them in central vision.

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