Perceived duration of chromatic and achromatic light.

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ABSTRACT

Luminance and color information are considered to be processed in parallel systems. The integration of information from these two separate systems is crucial for the visual system to produce a coherent percept. To investigate how luminance and color lights are perceived in time, we measured the perceived duration of light stimuli with and without colors in a paradigm involving simultaneous perception with presentation of two successive stimulus frames. Luminance contrast and color contrast of the stimuli were set with a chromatic substitution technique. In Experiment 1, the perceived duration of both chromatic stimuli and achromatic stimuli increased as the luminance contrast decreased. Experiment 2 tested if the duration of the percept was influenced by color contrast which was defined by colorimetric purity of the stimuli, when luminance contrast was set as low as practically possible. The result showed that the duration of the percept decreased with increasing color contrast of the stimuli. Moreover, Experiment 3 demonstrated that the trend of perceived duration was consistent with the four primary colors, provided that the effective color contrast of stimulus was corrected based on the contrast sensitivity to the color. These experiments indicate that, with a high luminance contrast level, perceived duration of a stimulus is predominantly defined by luminance contrast, whereas in low luminance contrast conditions, the duration depends on the color contrast. The perceived duration of color stimuli showed an “inverse color contrast effect,” similar to the well-known “inverse intensity effect” for luminance stimuli. The similarities and the differences between the two systems, as well as their priorities in processing temporal information of visual stimuli are further discussed.

Keywords:

temporal response, persistence, luminance, color, contrast, colorimetric purity

INTRODUCTION

It is known that the visual system processes color information slower than luminance information (De Lange, 1958; Mollon and Krauskopf, 1973; Kelly, 1983; Cavanagh, 1991). However, we never see color information persisting after the shape of objects disappears from perception, nor do we see colors smearing with a moving object. These observations from perception seem inconsistent with psychophysical evidence at threshold. Detection threshold of an incident light depends not only on the intensity, but also on its exposure duration. King-Smith and Carden (1976) showed that the temporal integration time was short for the luminance system and long for the opponent-color systems. If color information is processed slower than luminance information in the visual system, how does the visual system detect temporal coincidence between the two aspects of the stimuli? In the present study, we examined the property of visual mechanism how the temporal aspects of color (chromatic) and luminance (achromatic) information are processed.

The relative amplitude of luminance or color information can be defined by the "contrast" between the stimulus and the background. In the present study, we controlled the "contrast" of stimuli to activate both luminance- and color-processing systems so as to examine how the chromatic and achromatic amplitudes of stimuli influence their perceived duration. The duration of visual perception, also often referred to as visual or visible persistence, has been investigated as an index of human information processing and of how visual information is stored in the early visual system. A series of studies have found that visual persistence depends on the stimulus intensity (Allport, 1968; Haber & Standing, 1969; Efron & Lee, 1971; Bowen, Pola & Matin, 1974; Castet, Lorenceau & Bonnet, 1993), duration (Haber & Standing, 1970; Bowen, Pola & Matin, 1974; Bowling & Lovegrove, 1980), and background intensity (Allport, 1970; Dixon & Hammond, 1972; Hogben & DiLollo, 1985). The property that duration of the percept decreases with increasing intensity of test stimuli or increasing contrast between the test stimulus and its background field is referred to as the "inverse intensity effect" (Coltheart, 1980). However, in order to understand how visual persistence is affected by changes in color contrast and luminance contrast independently, we need to examine the temporal aspects of visual perception by using stimuli for which these parameters can be independently controlled. We have previously tested this question and reported the results elsewhere (Kawabata & Kojima, 1997). In the present study, we determined whether the inverse intensity effect of the duration of the percept holds true for stimuli with and without chromaticity. Furthermore, we investigated whether the duration of the percept is influenced by color contrast.

Several studies that have investigated whether visual persistence originates from persistent activity of receptors have used color stimuli and shown that perception of color persists longer than the estimated duration of the physiological response in cones (Banks & Barber, 1977; Adelson, 1978). The results indicate that chromatic persistence occurs beyond the photoreceptor level and suggest that the cortical system may function in temporal processing of color information. Bowen (1981) subsequently showed that 'visual offset latency', or visual persistence, of monochromatic stimuli with hue substitution was slower than that of incremental achromatic stimuli. This fact brings up the question how the perceived duration of chromatic stimuli would change if the chromatic and achromatic components of visual stimuli were varied independently.

We examined this question as a function of luminance contrast in Experiments 1 and of color contrast in Experiment 2. A further question is whether chromaticity itself contributes to the varying duration of persistence. Does the perceptual duration of chromatic stimuli vary as a function of chromatic amplitude (i.e., chromatic/color contrast)? In Experiment 2, we measured the perceived duration of chromatic stimuli using a chromaticity substitution technique (Bowen, 1981; Smith, Bowen & Pokorny, 1984). In Experiment 3, we examined whether the temporal properties of perception of chromatic stimuli were consistent across the four primary colors. These experiments consequently showed that the perceived duration of color stimuli depends on color contrast and luminance contrast in a similar way. We finally discuss how the two visual components from two separate systems are processed in time.

EXPERIMENT 1: Effect of Luminance Contrast

Method:

Apparatus and Stimuli

Stimuli were generated with a personal computer (NEC, PC-9801FA) with a graphic memory board (Digital Arts, HyPER-FRAME) and were presented on a 14-inch

CRT color monitor (NEC, KD1511) with 640 x 400 pixels and a 56.43-Hz (17.72 ms) refresh rate.

----- Figure 1 -----

One stimulus trial consisted of two display frames (F1 and F2) separated by an inter-stimulus interval (ISI). The ISI varied from 0.0 to 159.48 ms in nine equal steps. The durations of F1 and F2 were 35.44 ms each, which corresponded to two video frames of the monitor. F1 and F2 each contained an orthogonal pair of test lights (Ts) so that when both frames were superimposed, the two pairs of the test lights (four as a whole) appeared to be placed at each corner of a square. Figure 1 shows the schematic configuration of the stimulus presentation.

Each test light (T) had a circular shape with a diameter that subtended 1.0 arc deg and was convoluted with a Gaussian envelope with 1.0 deg standard deviation to reduce the transient component from the stimulus edge. The spatial separation between the each side of the Ts was also 1.0 deg. Ts were presented on a white background (B) which horizontally subtended 7.0 arc deg and vertically subtended 5.0 arc deg. The fixation point was placed at the center of the display.

The colors of the Ts were either white or red. The luminance contrast of each T was systematically changed. Table 1 shows the luminance intensities, the luminance contrasts between Ts and B, and the CIE chromaticity coordinates of the stimuli used in the present experiment. The CIE chromaticity coordinates and the luminance intensity of B were x = 0.31, y = 0.33 and 2.03 cd/m^2, respectively. The luminance intensity and the chromaticity coordinates were calibrated with a CRT Color Analyzer (Minolta, CA-100). The luminance contrast here was calculated using Michelson formula,

$$\text{Luminance contrast} = (L_{max} - L_{min}) / (L_{max} + L_{min})$$

where L_{max} and L_{min} are the luminance intensities of T and B, respectively.

In Results, we would also evaluate whether the temporal perception was depended on the temporal properties of photoreceptor response or of sub-cortical processing. To examine this possibility, the same data were represented as a function of Root Mean Square (RMS) cone contrast. RMS cone contrast of used stimuli was calculated by the following formula,

$$\text{RMS Cone Contrast} = \sqrt{[(Lc^2+Mc^2+Sc^2)/3]}$$

where Lc, Mc and Sc were the Weber cone contrasts for L, M and S cones (Nakano, 1996; Brainard, 1996).

----- Table 1 -----

Procedure

After ten minutes of dark adaptation, the subject sat in a darkened room 229 cm away from the CRT monitor and viewed a fixation point at its center with his head stabilized with a bite board. The stimuli were observed monocularly with the right eye through a 2-mm artificial pupil. An experimental session was initiated when the subject pressed any key on a computer keyboard. Each stimulus was presented following a brief warning buzzer. The subject's task was to indicate, with a keystroke, whether all four stimulus flashes were perceived simultaneously or not. The response to the stimulus started the next trial. The experiment proceeded with the method of constant stimuli. In this method, for each block, stimuli with 8 (or 9 for the lowest contrast conditions) ISIs were presented in random order. One experimental session consisted of 25 repetitions of the block. The experimental sessions for all contrast conditions were run twice within a week for both chromatic, red stimuli and achromatic, while stimuli.

Optical factors

The 2-mm artificial pupil, as used in the present study, increases the depth of focus enough to largely overcome the chromatic difference due to focusing. It seems unlikely that there would be any significant residual axial chromatic aberration for these stimuli when viewed through the pupil. Moreover, the dominant wavelength of the test stimuli was basically constant in the present experiments. Lateral chromatic aberration, related to the chromatic difference of magnification, was potentially a more serious problem. It cannot be overcome by using an artificial pupil. However, for a small stimulus presented relatively close to the optical axis, such as the stimuli used in the present study, the lateral aberration is probably negligible.

Subjects

The two authors (HK and YK), who were both experienced observers in studies of the temporal dynamics of perception, and one naïve undergraduate student (MM) participated in the experiment. All had normal visual acuity (VA > 1.2) and color vision as tested with Ishihara pseudoisochromatic plates, FM-100 hue test and Nagel-type anomaloscope (Hioki version, Handaya, Japan).

----- Figure 2 -----

Results:

The percentages that the four target lights were simultaneously perceived were shown as a function of ISI in Figure 2. All three subjects' results showed essentially the same trends. Thus, only the typical results with red stimuli for subject HK are shown. Each panel represents different luminance contrast conditions of Ts. As the contrast decreased, the distribution of the simultaneous perception shifted towards longer ISI, and the proportion of simultaneous perception moderately dropped with the ISI. A psychometric function was estimated by Probit analysis to the data in each panel, i.e. each contrast condition. The ISI corresponding to the mean (M), the duration at which 50 % of stimuli were perceived simultaneously, was taken as the threshold. The Ms and the standard deviations (SDs) of the each function are shown in Figure 3a as a function of luminance contrast. Some of the SD became longer when the luminance contrast of white stimuli was relatively low. The SD might reflect the variability or the easiness in perceptual decision-making, which is influenced by the visibility of the stimulus lights. Achromatic, white stimuli below 20% luminance contrast could not be tested because the stimuli were no longer visible, while chromatic, red stimuli with approximately 0% luminance contrast could still be tested.

----- Figure 3-----

The threshold duration of perceived lights increased for both chromatic and achromatic stimuli when the luminance contrast was low (Figure 3a). The result indicated that the "inverse intensity effect" held true whether or not chromaticity was involved in the stimuli. The perceived duration of a stimulus seemed to become longer as the contrast became lower and unclear to perceive. However, in the low luminance contrast condition, the perceived duration of chromatic (red) stimuli never became longer than that of achromatic (white) stimuli. This result may indicate that the "perceived contrast" of chromatic stimuli was kept from degrading, even when luminance contrast was no longer involved in the stimuli. It might indicate that chromatic information could contribute to temporal perception just as luminance contrast information. Thus, in the following experiment, we examined how the perceived duration of the stimuli changed as a function of color contrast, while controlling luminance contrast.

The present results were also expressed as a function of RMS cone contrast and examined whether the perceived duration showed a functional change with the cone contrast (Figure 3b). The results look scattered and intermixed with each other for luminance (WH) and color (RD) conditions. Although there was a slight tendency that the perceived durations were longer with luminance stimuli (WH) than those with color stimuli (RD), the figures showed that the perceived duration with both chromatic, red and achromatic, white stimuli were better expressed as a function of luminance contrast (Figure 3a) rather than RMS cone contrast (Figure 3b).

EXPERIMENT 2: Effect of Color Contrast

Method:

The spatial and temporal configurations of the stimuli were identical to those in Experiment 1 except that ISI was varied from 53.16 to 212.64 ms in nine equal steps and that Ts were changed as a function of color contrast instead of luminance contrast. In the present study, we defined color contrast as the distance ratio of T in the CIE diagram and the extended circumference point of T from B in the diagram. The derivation of the color contrast in this way is generally called “colorimetric purity”. The chromaticity of B was set to white identical to that of Experiment 1, and the color of Ts was systematically changed in the present experiment. Table 2 shows the color contrast, i.e. colorimetric purities, and the CIE chromaticity coordinates of stimuli employed in the present experiment.

Chromatic stimuli here were produced by means of the method called “chromatic substitution”. In this method, pure chromaticity modulation of the chromatic component of a test stimulus is performed by quickly substituting it for a portion of the background field which has the equivalent luminance but a different chromaticity. This design was similar to that of the previous studies of one of the authors (Kawabata, 1993, 1994). In the present experiment, the dominant wavelength (606 nm) of Ts was fixed.

The luminance intensity of each stimulus was set for each observer to minimize the luminance contrast. There are several variations of the equiluminance setting across experimental tasks and stimulus parameters, such as spatial and temporal frequencies of the stimuli (Cavanagh, Anstis & MacLeod, 1987; Livingstone & Hubel, 1987), and also across individuals (Kaiser, 1988). Here, we examined each subjects with the minimum flicker method (Cavanagh, 1991) to obtain their subjective lowest luminance contrasts at or around equiluminant conditions. Then, the luminance intensity at which the subject saw the slowest or weakest flicker was used as the luminance of Ts for his or her own trials. The same three subjects who participated in Experiment 1 served in this experiment.

----- Table 2 -----

Results:

Figure 4a shows the threshold perceived duration of chromatic lights as a function of color contrast of T. The trends of the results from three subjects look similar. The results clearly show that perceived duration of the stimuli increased with decreasing color contrast. Subject HK could not perform at the lowest condition, because the stimulus visibility, which would be reflected in the magnitude of SD, degraded with decreasing color contrast. Although the temporal range of perceived duration from three observers varies a little, the results were reasonable because, for each observer, the perceived durations with high color contrast in Experiment 2 showed almost the same values as those of red stimuli with low luminance contrast conditions in Experiment 1. Then, the perceived duration of the stimuli increased as color contrast decreased in Experiment 2, just as the perceived duration increased as luminance contrast decreased in Experiment 1.

----- Figure 4 -----

The manner of perceived duration, here, can be attributed to the color contrast, i.e. colorimetric purity, since the contribution of the achromatic component was negligible or at least minimized. However, the decrease of perceived duration with color contrast cannot be explained by optical factors. The focus of a chromatic light varies as a function of wavelength, though the dominant wavelength of Ts in the present experiment was kept unchanged for all test stimuli.

Figure 4b shows the results as a function of RMS cone contrast. The perceived duration showed a decreasing function with the RMS cone contrast, just as shown as a function of color contrast in Figure 4a. This result indicates that the perceived duration also depends on the magnitude of cone contrast in case of an equiluminant condition. However, one may wonder if the result was obtained because of the specific color (red) that used in this experiment. Thus, in the next experiment, we measured the perceived duration of stimuli with all four primary colors: red, green, blue and yellow.

EXPERIMENT 3 : Comparison of Colors

Method:

The spatial and temporal configurations of stimuli were identical to those in Experiment 2. All stimulus parameters were also the same as those in the previous experiments, except that the luminance intensity of B was set to 11.5 cd/m^2 so that all colors could be visible and tested at equiluminance. The colors tested in the experiment were red, green, blue and yellow. The dominant wavelengths of the colors were kept constant while the color contrasts, i.e. colorimetric purities (CP), of the stimuli were systematically changed as in Experiment 2. The stimulus parameters used for each color are summarized in Table 3. Fewer conditions could be tested with green and yellow because the CRT monitor used here had a limited dynamic range.

Two authors (HK, YK) and one naïve subject (MS) with normal color vision participated in the experiment. Subject MS could not accomplish the task with yellow and green color conditions.

----- Table 3 -----

Results:

The threshold for perceived duration was estimated as the mean of a psychometric function obtained from Probit analysis as in the previous experiments. However, the threshold values for different chromaticities could not be directly compared, since the visual response latency and/or temporal sensitivity of colors vary depending on chromaticity or wavelength (Bowen, 1981; Smith, Bowen & Pokorny, 1984). Thus, we measured the detection threshold (Th) of color contrast, i.e. CP, for each color used in this experiment (Table 4) and corrected the CP values by discounting with the threshold, CP/Th. The corrected color contrast can be thought as the practical color contrast of the used stimuli. Therefore, we represented the measured perceived durations as a function of the CP/Th.

----- Table 4 -----

Figure 5a showed that the threshold perceived durations of the color stimuli increased as the corrected color contrast decreased. The temporal properties of perceived duration for stimuli with any colors showed a similar trend and, as a whole, converged along a line.

----- Figure 5 -----

Figure 5b shows the same performances as a function of RMS cone contrast. The duration decreased with RMS cone contrast, especially within a low contrast range. The results in Figure 5a and 5b showed a certain similarity. However, the functions for each color stimuli in Figure 5b look more separate. On the contrary, the curves for all colors rather looks consistent when the results were expressed as a function of the corrected color contrast, CP/Th, rather than RMS cone contrast.

DISCUSSION

The first experiment showed that perceived duration of both chromatic and achromatic stimuli increased with decreasing luminance contrast. The results seem consistent with Bowen’s (1981) report that offset latency was shorter in the increment condition (of luminance) than in the hue substitution condition (with equiluminant color stimuli). His incremental condition corresponds to the high contrast condition with white stimuli in Experiment 1 in this study, while the substitution condition corresponds to the lowest luminance contrast condition with red stimuli in Experiment 1 and all conditions in Experiment 2. The present results showed that the perceived duration of lights had an inverse relationship with luminance contrast whether or not they involve chromaticity. In addition, the perceived duration of chromatic lights was shorter than that of achromatic stimuli in general, but it increased when the lights were presented with low luminance contrast or near equiluminance. It other words, the perceived duration was short when the lights has enough contrast in either luminance or color, and it became long when both contrasts were low. This fact indicates that the perceived duration of the stimuli depends on the total amount of contrast from the luminance and color.

The Experiment 2 showed that in equiluminance settings, the visibility deteriorated as the color contrast decreased and the perceived duration of stimuli increased. The result inferred that temporal processing of color contrast by chromatic system might be just as the way how luminance contrast was processed by achromatic, luminance system. Furthermore, Experiment 3 showed that the property of perceived duration was consistent over the variety of colors, provided that the effective color contrast was corrected based on each subject's sensitivity to the color used. Although our procedure for isolating the chromatic system depended on the assumption that the equiluminant setting cancels out the response of the luminance system (Mollon, 1980), the parameters used in the present experiments, at minimum, lessen the activation of the achromatic system in low luminance contrast conditions. Thus, the present study was considered to show a temporal processing property performed by the chromatic system. It has been reported that several types of neurons in the macaque primary visual cortex, which receive a different kind of opponent color inputs, also differ in temporal response (Cottaris and De Valois, 1998). The present results consistently showing that the temporal percepts of colors were better expressed in terms of the weighted colorimetric purity than in terms of cone contrast, suggest that there must be a cortical mechanism that corrects or modifies the differences of early temporal processing between colors.

The visual property that the perceived duration of a light increases with decreasing luminance contrast is known as the "inverse intensity effect," (Coltheart, 1980) which can be rephrased as the "inverse (luminance) contrast effect" when luminance contrast, instead of intensity, was used as the independent variable. Here, we found the "inverse color contrast effect," so to speak, in Experiments 2 and 3. Hence, the results infer that the well-known "inverse intensity effect" consists of two separate effects; "inverse luminance contrast effect" by achromatic system and "inverse color contrast effect" by chromatic system.

Previous studies reported that there was, in principle, a functional similarity between the chromatic coding system and the luminance coding system (De Valois & De Valois, 1988; Cavanagh, 1991; Kawabata, 1993, 1994). In the detection threshold level, the critical duration of temporal integration for chromatic stimuli decreased as a function of increasing background colorimetric purity (Kawabata, 1994). The present results revealed that both chromatic system and achromatic system have a similar property in temporal processing in suprathreshold. (i.e., perceived duration of a stimulus decreases both as a function of colorimetric purity as well as luminance intensity).

It has been previously shown that the temporal contrast sensitivity function (tCSF) of chromatic gratings show low-pass and low-cutoff frequency characteristics (De Lange, 1958; Kelly & van Norren, 1977; Kelly, 1983) and that the critical duration of temporal integration was longer for equiluminous chromatic stimuli than for luminance stimuli (Regan & Tyler, 1971; Smith et al., 1984; Kawabata, 1994). These results predict that visual responses can be sustained and persist longer for chromatic stimuli than for achromatic stimuli. Our results showing that the perceived duration of color stimuli around equiluminance was longer than those of luminance stimuli, are consistent with these previous studies. The results may also have a relationship with the phenomenon that the motion of equiluminant chromatic stimuli is perceived slower than motion of luminance stimuli (Cavanagh, Tyler & Favreau, 1984; Livingstone & Hubel, 1987; Burr, Fiorentini & Morrone, 1998). It was not explained by the differences in the perceived spatial frequency or in the perceived temporal frequency of the two types of stimuli (Henning & Derrington, 1994), but rather by the systematic difference of 1-D and 2-D motion perceptual systems (Farell, 1999). Then, Farell (1999) confirmed that motion is perceived slower with chromatic stimuli than luminance + chromatic stimuli. The report seems consistent with the present result that chromatic stimuli (Exp.2, Figure 4) were perceived longer (slower) than luminance + chromatic stimuli (Red stimuli in Exp.1, Figure 3a).

It has been shown that the visual system uses color information and luminance information cooperatively in spatial processing. Kingdom, Moulden and Collyer (1992) reported that, although spatial linking was minimal at equiluminance, color contrast provided enough information for linking spatial cues with luminance contrast information. Moreover, McIlhagga and Mullen (1996) have reported that both color and luminance information are used cooperatively in contour detection and have shown that performance is poorer when either of them is not useful. Similarly for visual temporal processing, the present results showed that although temporal performance was primarily determined by luminance information in high luminance contrast conditions, it became dependent on color information in low luminance contrast conditions where not enough luminance information was available. The present results are consistent with the idea in previous studies that luminance information has a priority, especially with object perception, but color information works as a supplement.

Although the chromatic and achromatic systems are independent to some extent, there is also evidence that the two systems interact asymmetrically (De Valois & Switkes, 1983; Switkes, Bradley & De Valois, 1988; Cole, Stromeyer & Kronauer, 1990). However, despite the fact that the organization of the color system in the lateral geniculate body (Wiesel & Hubel, 1966) and in the cortical visual pathway (Livingstone & Hubel, 1987, 1988; Cottaris & De Valois, 1998) has been investigated, we still have little neurological evidence for the mechanism behind how chromatic and achromatic information are combined. The properties and mechanisms of visual temporal integration of information from the separate systems, including both temporal binding and mis-binding of stimuli, have been extensively investigated (e.g., Singer & Gray, 1995; Kojima, 1998; Leonards & Singer, 1998; Wu, Kanai & Shimojo, 2004). Yet, how and where these systems interact to integrate visual information is an intriguing question that remains.

REFERENCES

Adelson, E. W. (1978). Iconic Storage: The role of rods. *Science*, **201**, 544-546.

Allport, D. A. (1968). Phenomenal simultaneity and the perceptual moment hypothesis. *British Journal of Psychology*, **59**, 395-406.

Allport, D. A. (1970). Temporal summation and phenomenal simultaneity: Experiments with the radius display. *Quarterly Journal of Experimental Psychology*, **22**, 686-701.

Banks, W. P. & Barber, G. (1977). Color information in iconic memory. *Psychological Review*, **84**, 536-546.

Bowen, R. W., Pola, J. & Matin, L. (1974). Visual persistence: Effects of flash luminance, duration and energy. *Vision Research*, **14**, 195-303.

Bowen, R. W. (1981). Latencies for chromatic and achromatic visual mechanisms. *Vision Research*, **21**, 1457-1466.

Bowling, A. & Lovegrove, W. (1980). The effect of stimulus duration on the persistence of grating. *Perception & Psychophysics*, **27**, 574-578.

Brainard, D. H. (1996). Part IV: Cone contrast and opponent modulation color spaces. In Kaiser, P. K. and Boynton, B. M. (Eds.), Human Color Vision. Second edition, pp.563-579. Optical Society of America: Washington, DC.

Burr, D. C., Fiorentini, A. & Morrone, M. C. (1998). Reaction time to motion onset of luminance and chromatic gratings is determined by perceived speed. *Vision Research*, **38**, 3681-3690.

Castet, E., Lorenceau, J. & Bonnet, C. (1993). The inverse intensity effect is not lost with stimuli in apparent motion. *Vision Research*, **33**, 1697-1708.

Cavanagh, P., Tyler, C. W. & Favreau, O. E. (1984). Perceived velocity of moving chromatic gratings. *Journal of the Optical Society of America*, **A1**, 893-899.

Cavanagh, P., Anstis, S. M. & MacLeod, D. I. A. (1987). Equiluminance: Spatial and temporal factors and the contribution of blue sensitive cones. *Journal of the Optical Society of America*, **A4**, 1428-1438.

Cavanagh, P. (1991). *Vision in equiluminance.* In Kulikowski, J. J., Walsh, V. & Murray I. J. (Eds.), Vision and Visual Dysfunction: vol.5 (pp. 234-250). London: Macmillan Press Ltd.

Cole,G. R., Stromeyer, C. F. III & Kronauer, R. E. (1990). Visual interactions with luminance and chromatic stimuli. *Journal of the Optical Society of America*, **A7**, 128-140.

Coltheart, M. (1980). Iconic memory and visible persistence. *Perception & Psychophysics*, **27**, 183-228.

Cottaris, N. P. & De Valois, R. L. (1998). Temporal dynamics of chromatic tuning in macaque primary visual cortex. *Nature*, **395**, 896-900.

De Lange, H. (1958). Research into the dynamic nature of the human fovea: Cortex systems with intermittent and modulated light. Attenuation characteristics with white and colored light. *Journal of the Optical Society of America*, **48**, 777-784.

De Valois, K. K. & Switkes, E. (1983). Simultaneous masking interactions between chromatic and luminance gratings. *Journal of the Optical Society of America*, **73**, 11-18.

De Valois, R. L. & De Valois, K. K. (1988). *Spatial Vision.* New York: Oxford Science Publication.

Dixon, N. F. & Hammond, J. (1972). The attention of visible persistence. *British Journal of Psychology*, **63**, 243-254.

Efron, R. & Lee, D. N. (1971). The visual persistence of a moving stroboscopically illuminated object. *American Journal of Psychology*, **84**, 365-375.

Farell, B. (1999). Color and luminance in the perception of 1- and 2-dimensional motion. *Vision Research*, **39**, 2633-2647.

Haber, R. N. & Standing, L. G. (1969). Direct measures of short-term visual storage. *Quarterly Journal of Experimental Psychology*, **21**, 43-54.

Haber, R. N. & Standing, L. G. (1970). Direct estimates of the apparent duration of a flash. *Canadian Journal of Psychology*, **24**, 216-229.

Henning, G. B. & Derrington, A. M. (1994). Speed, spatial-frequency, and temporal frequency comparisons in luminance and color gratings. *Vision Research*, **34**, 2093-2101.

Hogben, J. H. & DiLollo, V. (1985). Suppression of visible persistence in apparent motion. *Perception & Psychophysics*, **38**, 450-460.

Kaiser, P. K. (1988). Sensation luminance: A new name to distinguish CIE luminance form luminance dependent on an individual's spectral sensitivity. *Vision Research*, **28**, 455-456.

Kawabata, Y. (1993). Spatial integration properties in vision with chromatic stimuli. *Color Research and Application*, **18**, 390-398.

Kawabata, Y. (1994). Temporal integration at equiluminance and chromatic adaptation. *Vision Research*, **34**, 1007-1018.

Kawabata, Y. & Kojima, H. (1997). Visible persistence with chromatic and achromatic stimuli. Proceedings of the 8th Congress of International Color Association, 318-321. Kyoto, Japan. 25-30, May, 1997.

Kelly, D. H. (1983). Spatiotemporal variation of chromatic and achromatic contrast threshold. *Journal of the Optical Society of America*, **73**, 742-750.

Kelly, D. H. & van Norren, D. (1977). Two-band model of heterochromatic flicker. *Journal of the Optical Society of America*, **67**, 1081-1091.

Kingdom, F., Moulden, B. & Collyer, S. (1992). A comparison between colour and luminance contrast in a spatial linking task. *Vision Research*, **32**, 709-717.

King-Smith, P. E. & Carden, D. (1976). Luminance and opponent-color contributions to visual detection and adaptationand to temporal and spatial integration. *Journal of the Optical Society of America*, **66**, 709-717.

Kojima, H. (1998). Figure/ground segregation from temporal delay is best at high spatial frequencies. *Vision Research*, **38**, 3729-3734.

Leonard,U. & Singer, W. (1998). Two segmentation mechanisms with differential sensitivity for colour and luminance contrast. *Vision Research*, **38**, 101-109.

Livingstone, M. S. & Hubel, D. H. (1987). Psychophysical evidence for separate channels for perception of form, color, movement and depth. *Journal of Neuroscience*, **7**, 3416-3468.

Livingstone, M. S. & Hubel, D. H. (1988). Segregation of form, color, movement and depth: Anatomy, physiology, and perception. *Science*, **240**, 740-749.

McIlhagga, W. H. & Mullen, K. T. (1996). Contour integration with colour and luminance contrast. *Vision Research*, **36**, 1265-1279.

Mollon, J. D. (1980). Post-receptoral processes in color vision. *Nature*, **283**, 623-624.

Mollon, J. D. & Krauskopf, J. (1973). Reaction time as a measure of the temporal response properties of individual colour mechanisms. *Vision Research*, **13**, 27-40.

Nakano, Y. (1996). Part III: Color vision mathematics: A tutorial. In Kaiser, P. K. and Boynton, B. M. (Eds.), Human Color Vision. Second edition, pp.544-562. Optical Society of America: Washington, DC.

Regan, D. & Tyler, C. W. (1971). Temporal summation and its limit for wavelength change: An analog of Bloch’s law for color vision. *Journal of the Optical Society of America*, **61**, 1414-1421.

Singer, W. & Gray, C. M. (1995). Visual Feature Integration and the Temporal Correlation Hypothesis. *Annual Review of Neuroscience*, **18**, 555-586.

Switkes, E., Bradley, A. & DeValois, K. K.(1988). Contrast dependency and mechanisms of masking interactions among chromatic and luminance mechanisms. *Journal of the Optical Society of America*, **A5**, 1149-1162.

Smith, V. C., Bowen, R. W. & Pokorny, J. (1984). Threshold temporal integration of chromatic stimuli. *Vision Research*, **24**, 653-660.

Weisel, T. N. & Hubel, D. H. (1966). Spatial and chromatic interactions in the lateral geniculate body of the rhesus monkey. *Journal of Neurophysiology*, **29**, 1115-1156.

Wu, D.A., Kanai, R. & Shimojo, S. (2004). Steady-state misbinding of color and motion. *Nature*, **429**, 262.

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FIGURE CAPTIONS

Figure 1. (a) Schematic representation of the display of three successive frames. Two stimulus frames (F1 and F2) with a variable ISI frame inserted between them were presented. (b) A schematic representation of the display when the observer perceived the two stimulus frames simultaneously.

Figure 2. The percent of simultaneous perception that stimuli were simultaneously perceived in Experiment 1, was plotted as a function of ISI for each stimulus conditions. Only the results with red stimuli (Rd) for HK were shown. Other observers had similar trends. Psychometric functions, estimated with Cumulative normal distributed functions, were fitted by Probit Analysis. The mean of the function was defined as the threshold duration of simultaneous perception to the stimulus.

Figure 3. (a) Threshold perceived durations of stimuli, in Experiment 1, were shown as a function of luminance contrast for each observer. Error bars indicate the standard deviations of the psychometric functions for the distributions. (b) The same, threshold perceived durations, were plotted as a function of RMS cone contrast.

Figure 4. (a) The estimated perceived durations of stimuli in Experiment 2 were plotted as a function of the rate of color contrast. Error bars indicate the standard deviations of the psychometric functions. (b) The perceived durations were shown as a function of RMS cone contrast.

Figure 5. (a) The threshold perceived durations of stimuli were shown as a function of the corrected color contrast, i.e. colorimetric purity (CP) corrected by the detection threshold (Th) or CP/Th. (b) The same data of perceived duration were plotted as a function of RMS cone contrast.

TABLE CAPTIONS

Table 1. The luminance intensities, luminance contrasts and CIE chromaticity coordinates of the test stimuli (Ts) used in Experiment 1 were listed. Seven luminance contrasts were used for the achromatic, white stimuli (open circle and open square in the CIE chromaticity space) and eight luminance contrasts were used for the chromatic, red stimuli (x points and a cross in the CIE space). The white background field (B) had a CIE coordinate of x = 0.31 and y = 0.33 and an intensity of 2.03 cd/m^2.

Table 2. The color contrasts (colorimetric purity) and CIE chromaticity coordinates for the stimuli (asterisks in the CIE space) used in Experiment 2, are shown with the condition used as a background (an open circle in the CIE space).

Table 3. Dominant wavelength and colorimetric purities (CPs) of the test stimuli (Ts) used in Experiment 3 are listed in Table and shown in the CIE space (Red: open circles, Green: open triangles, Blue: open stars, Yellow: open hexagrams). The white background (an open circle in the CIE space) was set as CIE chromaticity coordinates x = 0.31 and y = 0.33, and its luminance intensity was 11.5 cd/m^2.

Table 4. Detection thresholds (Th) of color contrast by means of colorimetric purity for each colors used in Experiment 3, are shown for each subjects.

Table

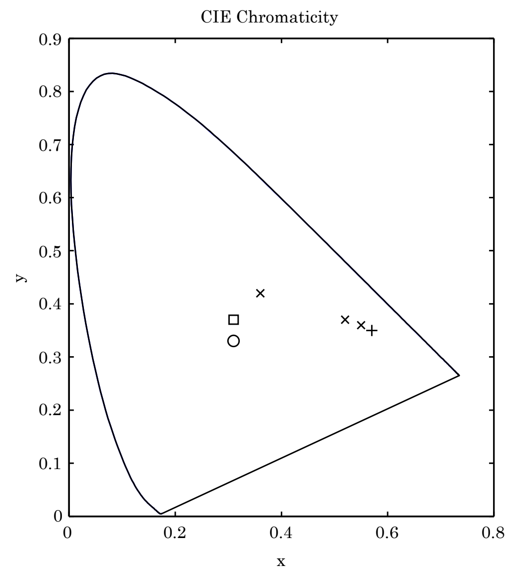
Table 1

Stimulus color: WHITE

Stim.No.	Lum.Intensity (cd/m^2)	Lum. Contrast(%)	CIE coordinate (x, y)
WH 0	0.50	-61	(0.31, 0.37)
WH 1	1.08	-30	(0.31, 0.33)
WH 2	1.31	-20	(0.31, 0.33)
WH 3	2.99	+20	(0.31, 0.33)
WH 4	3.78	+30	(0.31, 0.33)
WH 5	8.05	+60	(0.31, 0.33)
WH 6	30.40	+87	(0.31, 0.33)

Stimulus color: RED

Stim.No.	Lum.Intensity (cd/m^2)	Lum. Contrast(%)	CIE coordinate (x, y)
RD 0	0.48	-61	(0.36, 0.42)
RD 1	1.09	-30	(0.52, 0.37)
RD 2	1.67	-10	(0.55, 0.36)
RD 3	2.05	+ 1	(0.57, 0.35)
RD 4	2.47	+10	(0.57, 0.35)
RD 5	3.76	+30	(0.57, 0.35)
RD 6	8.09	+60	(0.57, 0.35)
RD 7	30.40	+87	(0.57, 0.35)



Background Color: WHITE

Luminance Intensity	CIE coordinate(x, y)
2.03 (cd/m^2)	(0.31, 0.33)

Table

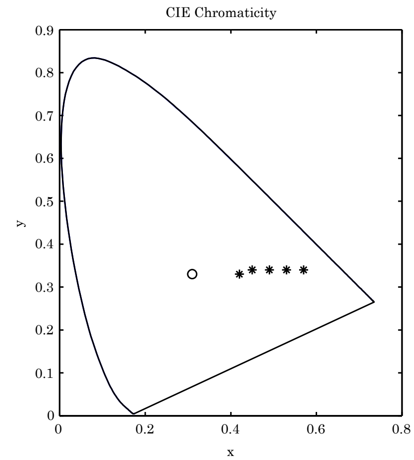
Table 2

Stimulus Color : RED, Dominant wavelength = 606 (nm)

Stim.No.	Color Contrast (Colorimetric Purity)	CIE coordinate (x, y)
CP 1	0.334	(0.42, 0.33)
CP 2	0.420	(0.45, 0.34)
CP 3	0.552	(0.49, 0.34)
CP 4	0.665	(0.53, 0.34)
CP 5	0.794	(0.57, 0.34)

Background Color: WHITE

Lum. Intensity	CIE coordinate (x, y)
2.03 (cd/m^2)	(0.31, 0.33)

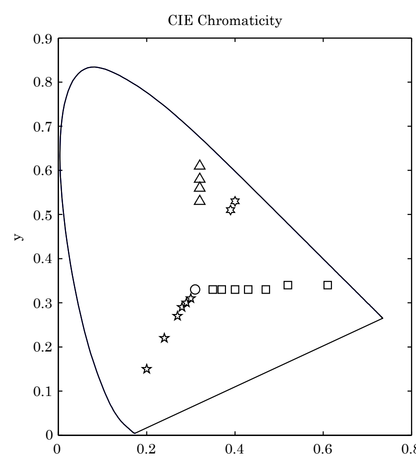


Table

Table 3

Stimulus Color	Dominant Wavelength (nm)	Stimulus No. & Colorimetric Purity						
RED	608	r1 0.1.06	r2 0.170	r3 0.251	r4 0.356	r5 0.464	r6 0.599	r7 0.871
GREEN	553	g1 0.583	g2 0.668	g3 0.743	g4 0.817			
BLUE	466	b1 0.061	b2 0.105	b3 0.146	b4 0.199	b5 0.379	b6 0.611	
YELLOW	567	y1 0.741	y2 0.826					

Background Color: WHITE	Lum. Intensity	CIE coordinate (x, y)
	11.5 (cd/m^2)	(0.31, 0.33)



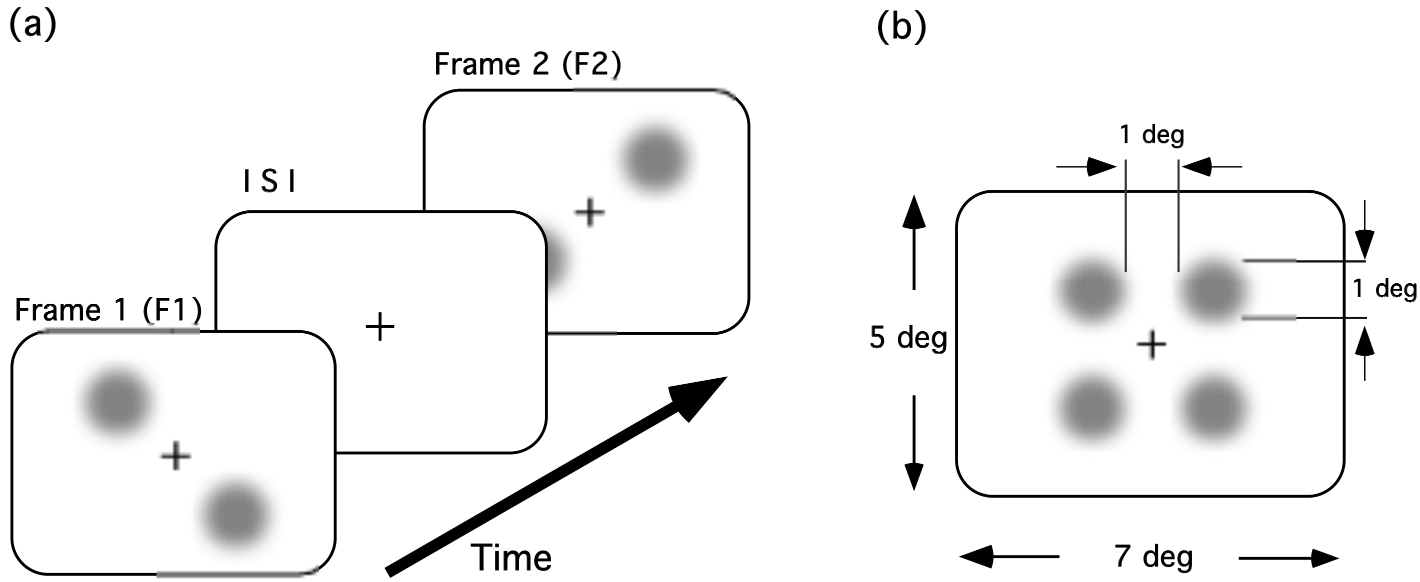
Table

Table 4

Detection Thresholds of Stimuli in Colorimetric Purity

Color	Subject		
	HK	YK	MS
RED	0.084	0.076	0.082
GREEN	0.514	0.421	0.442
BLUE	0.040	0.039	0.042
YELLOW	0.622	0.532	0.644

Figure



Figure

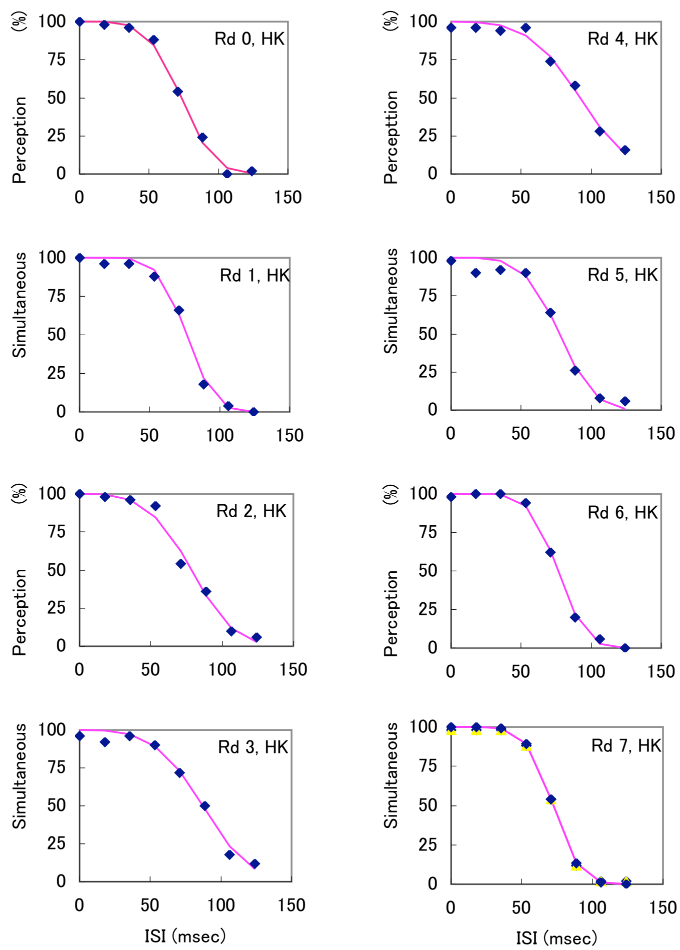


Figure 2

Figure

Figures3

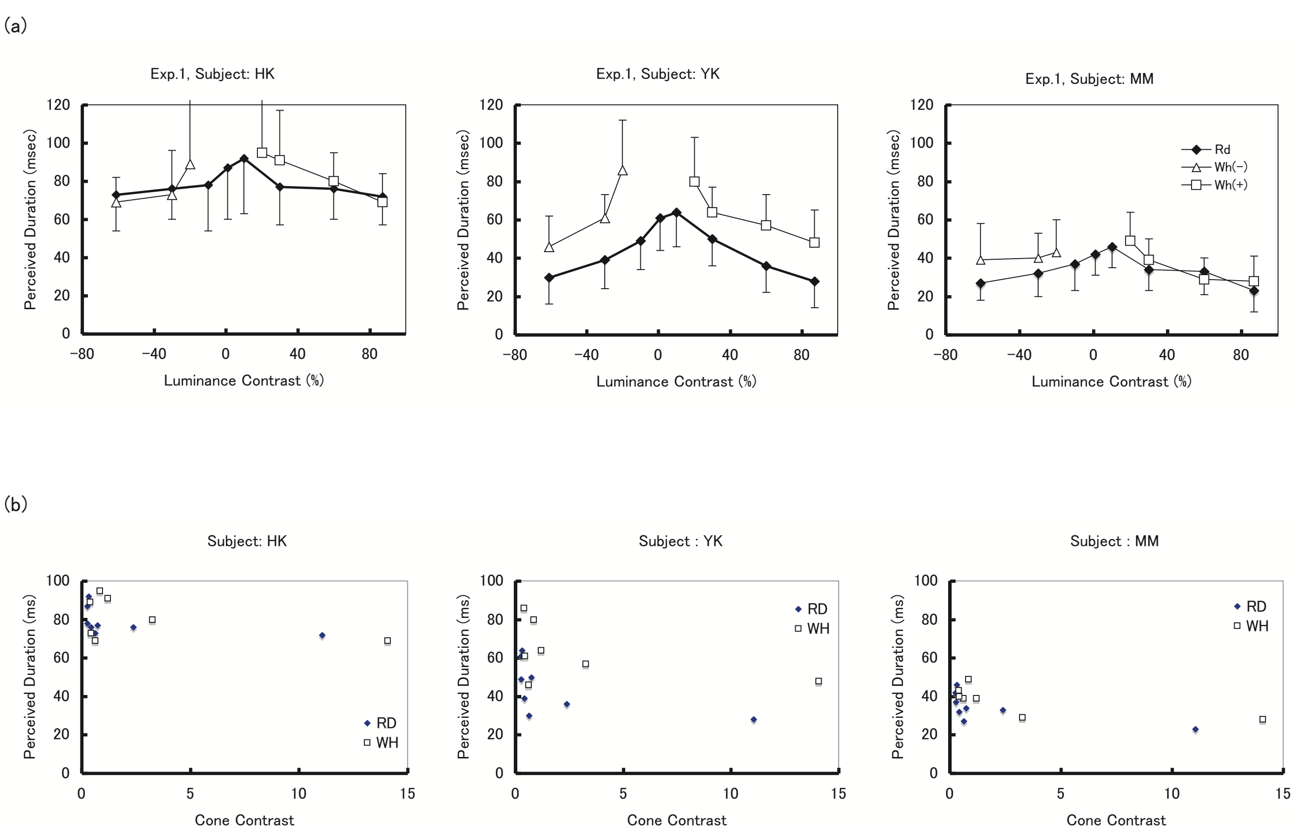
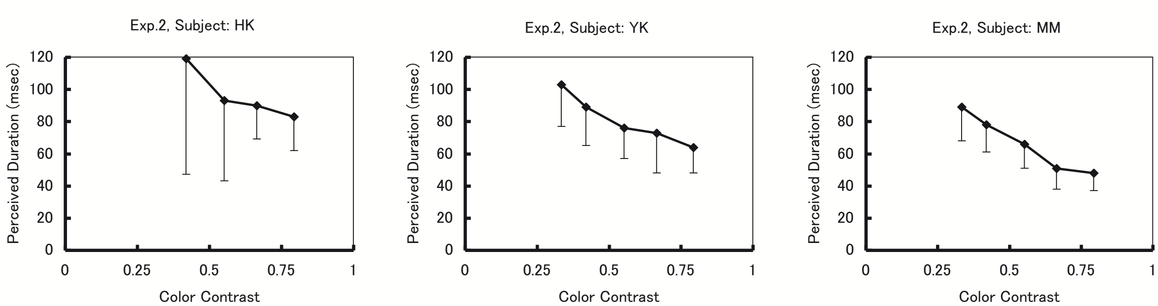


Figure 3

Figure

(a)



(b)

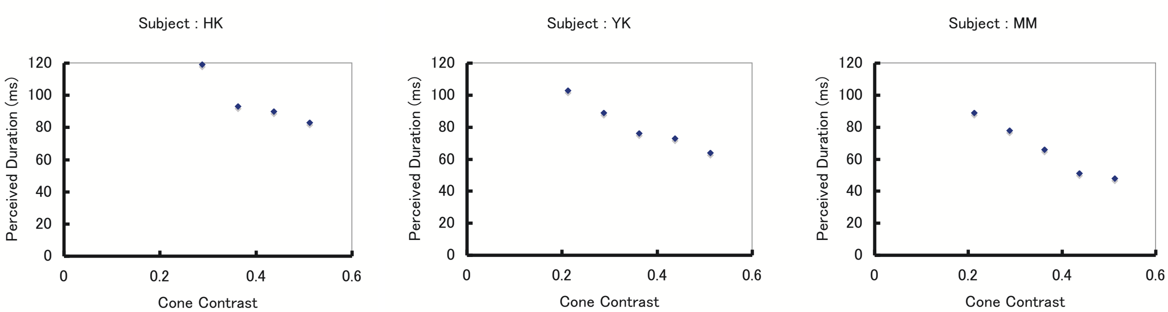


Figure 4

Figure

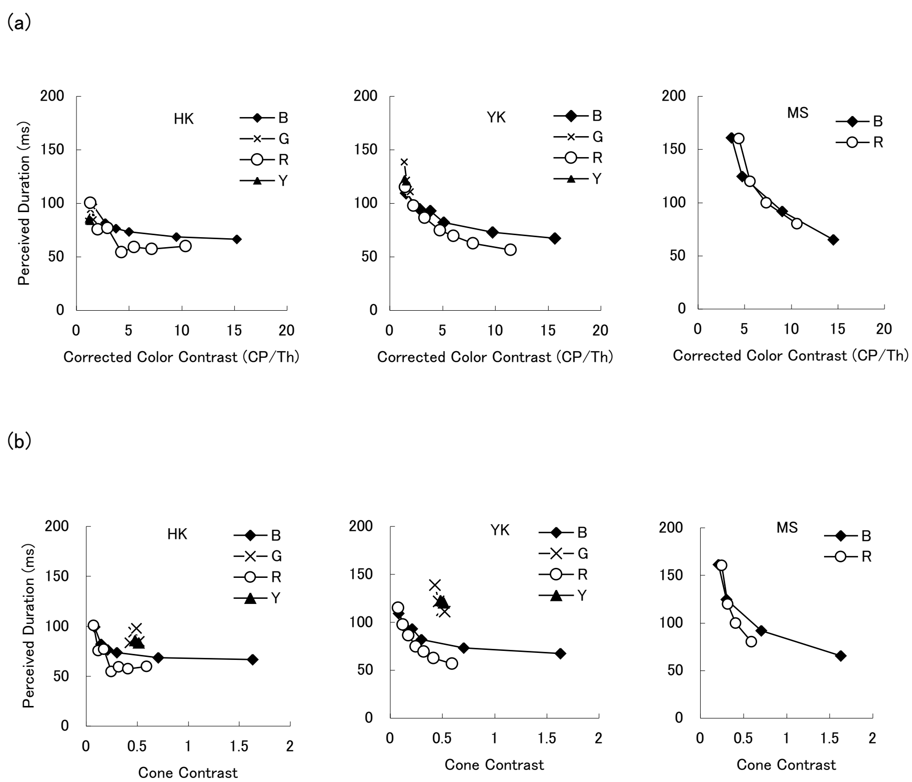


Figure 5