Effects of visual attention on chromatic and achromatic detection sensitivities

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Visual attention has a significant effect on various visual functions, such as response time, detection and discrimination sensitivity, and color appearance. It has been suggested that visual attention may affect visual functions in the early visual pathways. In this study we examined selective effects of visual attention on sensitivities of the chromatic and achromatic pathways to clarify whether visual attention modifies responses in the early visual system. We used a dual task paradigm in which the observer detected a peripheral test stimulus presented at 4 deg eccentricities while the observer concurrently carried out an attention task in the central visual field. In experiment 1, it was confirmed that peripheral spectral sensitivities were reduced more for short and long wavelengths than for middle wavelengths with the central attention task so that the spectral sensitivity function changed its shape by visual attention. This indicated that visual attention affected the chromatic response more strongly than the achromatic response. In experiment 2 it was obtained that the detection thresholds increased in greater degrees in the red–green and yellow–blue chromatic directions than in the white–black achromatic direction in the dual task condition. In experiment 3 we showed that the peripheral threshold elevations depended on the combination of color-directions of the central and peripheral stimuli. Since the chromatic and achromatic responses were separately processed in the early visual pathways, the present results provided additional evidence that visual attention affects responses in the early visual pathways.

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1. INTRODUCTION

It is well known that visual attention has significant effects on various visual functions, such as response time, sensitivity of detection and discrimination, and color appearance [1–4]. Some previous psychophysical and physiological studies suggested that visual attention could affect visual functions in the early visual pathways [3–6]. Carrasco and her colleagues found that transient attention affected spatial and temporal vision in the early visual processes in contrast sensitivity, spatial resolution, apparent contrast, and color appearance [2,7–9] as well as sustained attention [10]. It was reported in physiological experiments that attention modulated neural activity in the early visual systems. O'Connor *et al.* revealed that the attention enhanced neural responses to attended stimuli and attenuated responses to ignored stimuli in the human lateral geniculate nucleus (LGN) [11] as well as visual cortex V1 to V4 [11–14].

It is generally accepted that the increment-threshold spectral sensitivity reflects the chromatic and achromatic responses in the early visual pathways, i.e., cone opponent channels [15–17]. The spectral sensitivity function, measured with increment thresholds, has three peaks in the short, middle, and long wavelength regions in a fairly strong white adaptation condition. It is explained that these three peaks are caused by red–green (r/g) and yellow–blue (y/b) chromatic responses, which are more sensitive than achromatic responses to those wavelengths. Uchikawa *et al.* reported, as results of experiments using a dual task paradigm, that the spectral sensitivity function, measured by increment threshold, changed in shape so that the three peaks at short, middle, and long wavelengths became more prominent when stronger attention was paid to the test stimulus [5]. This difference in shape of the spectral sensitivity function indicated that the visual attention enhanced the chromatic component more than the achromatic component. The similar changes in shape of the spectral sensitivity were also reported in Uchikawa and Sato [18] and Smith *et al.* [17]. These studies proved that the increment-threshold spectral sensitivity was useful for measuring relative contributions of the chromatic and achromatic responses to a certain visual function.

Morrone *et al.* showed by a dual task paradigm that the peripheral contrast thresholds, either for luminance or chromatic, deteriorated only when the observer simultaneously performed the same modality (luminance or chromatic) task in the central field. This indicated that the attention interference was only effective either in the luminance or the chromatic dimension [6]. Uchikawa *et al.*, however, showed that both the chromatic and luminance contrast sensitivities were reduced in the periphery when the visual task was achromatic, suggesting no modality specificity of visual attention to luminance or chromatic dimension [5].

It has been reported in some previous studies that visual attention could be paid to a particular color. Brawn and Snowden showed that observers could selectively attend to items on the basis of color [19]. Blaser *et al.* reported that the endogenous attention to a color drastically altered the salience of that color, although it did not change the color appearance [20]. Fuller and Carrasco showed that the exogenous attention increased the apparent saturation of the colored stimuli, but it did not change their apparent hue [9]. Andersen *et al.* obtained the results that color-selective attention produced a sensory gain enhancement at the early levels of the visual cortex [21]. Prinzmetal *et al.* showed that the attention had little effect in changing the way objects appeared in terms of the observer's mean response, but the attention reduced the variability of the responses [22]. Although these studies showed that the visual attention specifically worked on color as a stimulus feature, it is not clear yet whether the visual attention might affect the chromatic and achromatic responses in the visual system differently.

The purpose of this study is to clarify whether visual attention modifies responses in the early visual system. We examined selective effects of visual attention on sensitivities of the chromatic and achromatic responses that were assumed as separately processed in the early visual pathways. If we could find that the chromatic and achromatic responses are differently affected by visual attention, this would mean that attention modifies neural responses in the early visual pathways, such as LGN or V1. It is known that a dual task paradigm is a useful method to investigate the effects of attention on stimuli presented in spatially separated areas. In the present experiments we used the central and peripheral stimuli in a single task and dual task condition. We measured increment-threshold spectral sensitivity functions in experiment 1 and increment detection sensitivities in the red/green (r/g) and yellow/blue (y/b) directions in experiment 2 for peripheral stimuli with and without a central attention task. In experiment 3 we measured the chromatic and achromatic contrast thresholds with a certain pedestal contrast both for central and peripheral stimuli.

2. GENERAL METHOD

A. Apparatus

The stimuli, generated using the VSG graphics card (Cambridge Research Systems) mounted in a Windows PC, were presented on a 22-in. CRT display [Mitsubishi, RDF221H (experiment 1) and Iiyama, MS103 (experiments 2 and 3)]. In experiments 1 and 2, an additional white background, produced by a light box (Hakuba, KLV-9000), was added using a half-mirror on the CRT screen in order to increase the background luminance. The background was white, subtended 42.6 deg × 32.6 deg, as shown in Fig. 1(a). The chromaticities and luminance, respectively, were $(x = 0.329,\ y = 0.344)$, 136 $\mathrm{cd/m^2}$ in experiment 1 and $(x = 0.330,\ y = 0.352)$, and 132 $\mathrm{cd/m^2}$ in experiment 2. In experiment 3 we removed the additional background to make it possible to present the high-contrast chromatic and achromatic stimuli. The background was white $(x = 0.317,\ y = 0.359)$ and 33.3 $\mathrm{cd/m^2}$. The viewing distance was 57 cm in all experiments.

B. Observers

Three observers (a male and two females) participated in experiment 1, six observers (two males and four females) in experiment 2, and seven observers (three males and four females) in experiment 3. All nine observers in total had normal color vision as tested by an Ishihara Color Plate. The first author participated in all the experiments, the second author only in experiment 2, and the third author in both experiments 2 and 3. The other observers were naïve as to the purpose of the experiments.

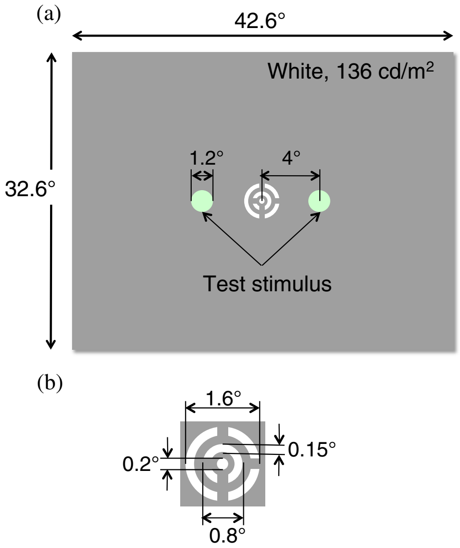

Fig. 1. Stimulus configurations used in experiments 1 and 2. (a) A circular test stimulus was presented either on the left or the right from the central fixation point in the peripheral visual field. Increment thresholds were measured in a single task condition in which the observer paid attention only to the test stimulus. They were also measured in a dual task condition in which the observer performed both the central task and the peripheral task. (b) A pattern stimulus with two concentric rings was used for the central attention task. The observer's task was to respond to the number of rings with two gaps.

3. EXPERIMENT 1

A. Stimulus and Procedure

We employed a dual task paradigm in these experiments. The observer paid visual attention to either only a peripheral visual field (single task) or to both a central and a peripheral visual field (dual task). We measured the detection thresholds for a peripheral stimulus in a single task and a dual task condition. The threshold elevation for a peripheral stimulus, caused by reducing the visual attention to the peripheral stimulus due to the central attention task, was used as an index of the attention effects on detecting the peripheral stimulus.

The peripheral test stimulus was a circle of 1.2 deg in diameter. It was presented with the eccentricity of 4 deg either to the right or to the left from a central fixation point [Fig. 1(a)]. A central task stimulus was a pattern consisting of two rings, as shown in Fig. 1(b). It was presented around a fixation point on the central visual field. Each ring of the central task stimulus had four possible gap positions. The observer's task was to respond to the number of the rings that had two gaps. In the example shown in Fig. 1(b), the inner ring has two gaps and the outer ring has three gaps. In this case the correct answer is 1. Thus, the possible answers are 0, 1, or 2. The contrast of the rings was adjusted to the threshold contrast for a 66% correct response, which was determined in a preliminary experiment when the observer only performed the central task. The fixation point subtended 0.2 deg.

In a trial, the observer looked at the fixation point and, when ready, he or she pressed a start key to present the central task stimulus. The central stimulus appeared for

1.5 s, then the peripheral stimulus was presented for 100 ms with stimulus onset asynchrony (SOA) of 400 ms. The observer's peripheral task was to respond to the position of the stimulus in two-alternative forced-choice (2AFC). In a session including the central attention task we instructed the observer to pay attention to the central stimulus with the highest priority. Only when the observer responded correctly to the central task the observer could respond to the peripheral task. In a session with no central attention task the observer only responded to the peripheral task. The central stimulus also appeared in this session, but the observer ignored the central stimulus. We used a double staircase method to change the contrast of the peripheral stimulus for each trial. The staircase ended when 15 reversals were obtained. The 75% threshold was determined by the probit analysis using the cumulative response function.

It is possible to obtain an "equivalent" spectral sensitivity function of the increment threshold, not with monochromatic lights on a white background but with compound stimuli made by r, g, and b phosphors of a CRT monitor. An increment monochromatic light on a white background has a combination of L, M, and S cone responses. The same L, M, and S combination can be made with a metameric compound colored-light in a certain range of L, M, and S responses. We used the L, M, S cone fundamentals of Stockman *et al.* [23] to convert the mixture of a monochromatic light and the white background to the corresponding compound light. The "wavelength" of the peripheral stimulus was set at 420, 440, 460, 480, 500, 520, 540, 560, 570, 580, 600, 620, 640, 660, or 680 nm.

B. Results and Discussion

The four top panels in Fig. 2 show the log spectral sensitivity functions for three observers and the average functions of the observers. Closed and open symbols correspond to conditions with and without the central attention task, respectively. In the bottom panel the log threshold elevations, i.e., differences in the log threshold sensitivities between these two conditions, are plotted for each wavelength. Two-way analysis of variance (ANOVA) for the spectral sensitivity functions showed that an interaction effect of the wavelength and task condition was statistically significant [F(14, 28) = 5.380,

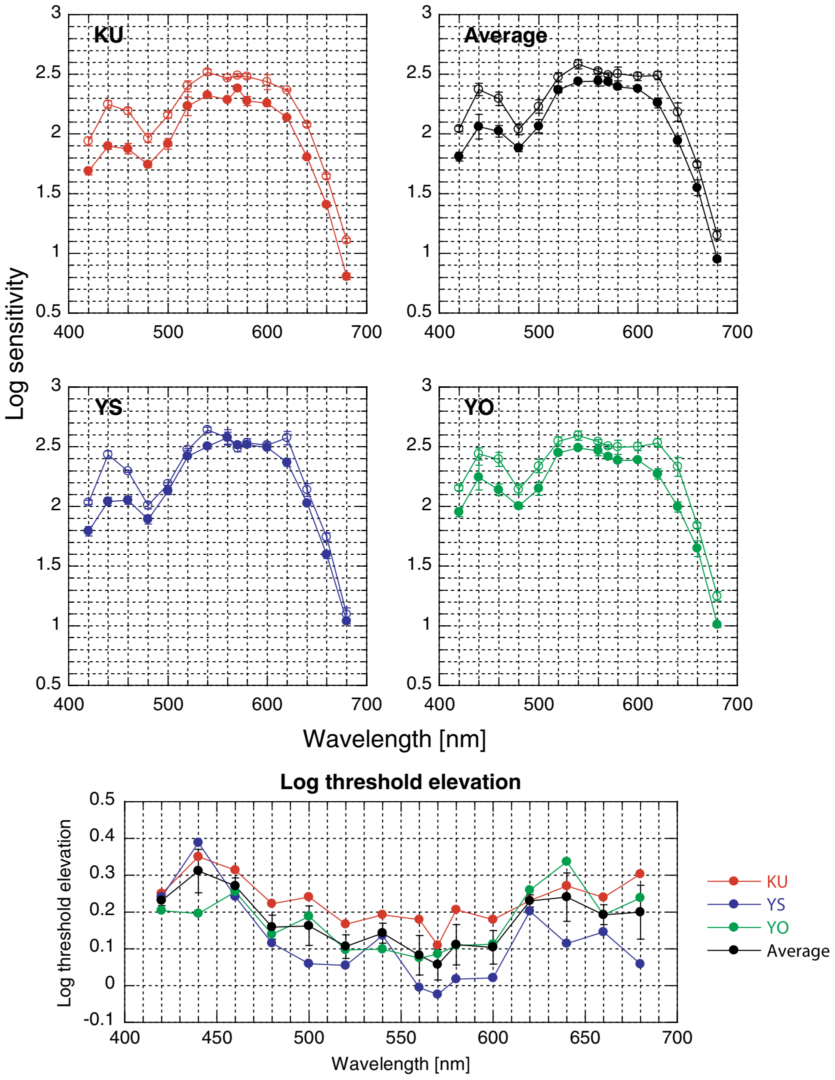

Fig. 2. Top panels: increment spectral sensitivity functions in the periphery for three observers and the average. Bottom panel: log threshold elevation for detecting the peripheral stimulus caused by the central attention task.

$p = 0.001$]. To examine the differences between the task conditions, we ran a one-way ANOVA for the average of the log threshold elevations. It showed that the main effect of the wavelength was statistically significant [$F(14, 28) = 5.359$, $p = 0.0001$], and that the threshold elevation for 440 nm was significantly different from those for 520, 560, 570, 580, and 600 nm. The threshold elevation for 460 nm was also significantly different from those for 560 and 670 nm, and the threshold elevation for 640 nm was different from that for 570 nm by the multiple comparison tests using Ryan's method ($\alpha = 0.05$).

We examined whether the performance of the central task depended on the peripheral wavelengths. The average percentage correct was 76.1% for all observers, ranging from 73.8% to 78.7% across wavelengths. No systematic difference was found across wavelengths, indicating no variable tradeoff between the central and peripheral tasks as a function of peripheral wavelength.

It is obvious in these results that the spectral sensitivities for the short wavelengths and long wavelengths were reduced to a greater degree than for middle wavelengths by less attention directed to the peripheral stimuli. This change in the spectral sensitivity function is consistent with the previous report [5]. It is generally accepted that stimuli of short wavelengths (440–460 nm) and long wavelengths (640–660 nm) have more chromatic contribution than those of middle wavelengths (560–570 nm) to stimulus detection [15,24]. This means that larger differences in the spectral sensitivity for short and long wavelengths indicate greater loss of chromatic contribution relative to achromatic contribution, suggesting that the visual attention affected the chromatic response more strongly than the achromatic response in the visual system.

Two possible hypotheses might be conceived to explain the results of experiment 1. One would be that the chromatic system needs a greater amount of attention resources than the achromatic system to detect a colored stimulus. Therefore, when less attention was paid to the stimulus, the chromatic system lost greater sensitivity than the achromatic system. The other would be that, in experiment 1, the attention became less effective for the chromatic system in the periphery since the central task stimulus was achromatic. The feature-based attention to "achromatic" enhanced the achromatic system in the whole visual field so that the activities of the chromatic system decreased relatively. Our hypotheses cannot explain the results of Morrone *et al.* [6]. They reported that the achromatic central task did not affect the chromatic peripheral task. They also showed, using a chromatic central stimulus, that the chromatic central task did not affect the achromatic peripheral task. In experiment 2 we examined whether a chromatic central task would affect an achromatic peripheral task, as shown in Morrone *et al.*, as well as tested our hypotheses.

4. EXPERIMENT 2

A. Stimulus and Procedure

In experiment 1 we used only white rings for a central task. In order to test the two hypotheses proposed, to explain the results in experiment 1, we used a chromatic stimulus for the central task. Moreover, to find any agreement between Morrone *et al.* and our results, it was necessary to make our experimental conditions similar to their conditions. We employed chromatic rings in addition to white rings for the central task stimulus in experiment 2.

In experiment 2 we measured detection thresholds along the chromatic [$L - M$ and $S - (L + M)$] and achromatic ($L + M + S$) axes in a cone-opponent color space to more directly reveal the attention effects on the chromatic and achromatic responses. The same stimulus configuration was used as in experiment 1. We added the chromatic central stimulus, which was produced by chromatic change with equal luminance. The time course of stimulus presentation and the observer's response were the same as in experiment 1. The observer also performed a control condition with no central task to obtain reference thresholds.

As chromatic stimuli we used increment and decrement stimuli along the $L - M$ axis (noted as red and green) and those along the $S - (L + M)$ axis (called blue and yellow). They were equated in luminance ($L + M$) to the white background. The achromatic increment and decrement (called white and black) were also used. We made the peripheral stimulus using the six directions and the central rings using the red, green, and white directions. The L, M, S cone fundamentals of Stockman *et al.* [23] were used to make the stimuli.

B. Results and Discussion

Figure 3 shows the log threshold elevations for detecting the peripheral stimulus along six increment or decrement directions in the cone-opponent color space. In the top panel, the log threshold elevations are separately shown for three central stimulus color-conditions, i.e., white, red, and green, which are indicated by different color symbols. The bottom panel shows the average across the three central conditions.

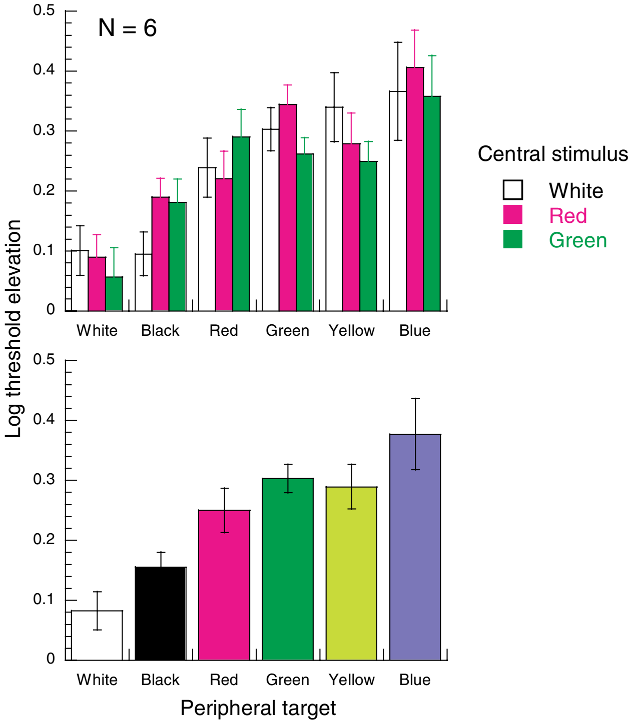

Fig. 3. Log threshold elevation for detecting the peripheral stimulus caused by the central attention task. Top panel: log threshold elevations are shown for three central stimulus color-conditions. Bottom panel: average across the three central conditions.

We used two-way ANOVA to examine any significant difference in the log threshold elevations in the top panel of Fig. 3. The main effect of the peripheral stimulus color-direction was statistically significant $[F(5,25) = 20.084,\ p < 0.0001]$. The central stimulus color-conditions did not have a significant difference $[F(2,10) = 2.035,\ p = 0.1814]$. The interaction between the central stimulus color-condition and the peripheral stimulus color-direction was not significant $[F(10,50) = 1.089, p = 0.3884]$. The multiple comparison tests using Ryan's method ($\alpha = 0.05$) showed that the log threshold elevations for the chromatic peripheral stimuli (red, green, yellow, and blue) were significantly different from those for achromatic peripheral stimuli (white and black). The difference in the log threshold elevation between the red and blue was also significant.

We tested whether performance of the central task depended on the peripheral stimulus color-directions. The average percentage correct of the central task was 68.2% for all six observers, ranging from 66.9% to 70.0% across wavelengths. No systematic difference was found across the peripheral stimulus color-directions, indicating no variable trade-off between the central and peripheral tasks as a function of peripheral stimulus color-direction.

We confirmed in experiment 2 that the chromatic detection thresholds of the peripheral stimulus increased more than its achromatic thresholds in the cone-opponent color space when the observer paid visual attention to the central stimulus. This attention effect is consistent with the findings in experiment 1. Another clear result obtained in experiment 2 is that the detection thresholds of the peripheral stimulus were not influenced by the central stimulus colors. This result may reject the second hypothesis and support the first hypothesis that the chromatic system needs a greater amount of attention resources than the achromatic system to keep the performance level constant.

We again obtained results that were inconsistent with Morrone *et al.* One of the major differences between Morrone *et al.*'s and our experimental conditions is that our central task was to detect the spatial gaps in the rings drawn by lines with either chromatic or achromatic borders, whereas Morrone *et al.* used a visual search as their central task in which the observer reported the presence or absence of a small target difference either in chromatic or achromatic contrast from distractors. Our central task was pattern discrimination while their central task was contrast discrimination. The peripheral task was to detect the chromatic or achromatic contrast in both experiments, although our stimulus was a single circle whereas their stimulus was a grating. It would be the case that the type of central task was a critical factor that could influence the contrast threshold of the peripheral stimuli. Therefore, in experiment 3 we used a contrast discrimination task that was the same for the central and peripheral tasks in order to test whether differences in central tasks could yield any significant difference in the chromatic and achromatic detection thresholds of peripheral stimuli.

5. EXPERIMENT 3

A. Stimulus and Procedure

In experiment 3, as shown in Fig. 4, the central task stimulus consisted of eight disks of 0.6 deg diameter, presented at an eccentricity of 1 deg. The peripheral stimulus also consisted of eight disks of 1.2 deg diameter, presented at an eccentricity of 4 deg. The central and peripheral stimuli were simultaneously presented for 200 ms. We used pedestals for both the central and peripheral stimuli in experiment 3. The pedestal luminance, or chromatic contrast, was set to be four times higher than the detection contrast, which was measured in a preliminary experiment for each observer. One of the central eight disks, chosen at random as a central stimulus, had a higher contrast than the other central disks. A peripheral stimulus was determined in the same way. The observer's task was to respond to a position of the stimulus by eight-alternative forced-choice (8AFC) for both the central and peripheral stimuli.

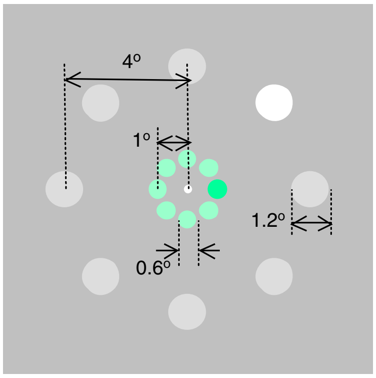

Fig. 4. Stimulus configuration used in experiment 3. Both central and peripheral stimuli consisted of eight disks. The observer's task was to detect the stimulus with higher contrast than the other seven distractors both for the central and the peripheral stimulus.

In the dual task condition, the observer first responded to the central task, then s/he responded to the peripheral task. In the single task condition, the observer only responded either to the central task or to the peripheral task. Increment thresholds obtained in the dual task condition were divided by those obtained in the single task condition to calculate the threshold elevation.

We selected four color-directions in the cone-opponent color space used in experiment 2: white, red, green, and blue, both for the central and peripheral stimuli. Threshold elevations were obtained for a combination of central and peripheral color directions in three groups. Group (a) was composed of the same color directions for central and peripheral stimuli (white, red, green, and blue); Group (b) was composed of different chromatic directions between central and peripheral stimuli (red versus green and green versus blue); and Group (c) was composed of achromatic and chromatic directions for central and peripheral stimuli (white versus green and white versus blue). Each group consisted of four combinations.

B. Results and Discussion

Figure 5 shows the results in a scattering diagram that plots the average log-threshold elevations for the peripheral stimulus on the ordinate and that for the central stimulus on the abscissa in the dual task condition. The outer and inner colors of a symbol correspond to color directions of the peripheral and central stimulus, respectively. Alphabetical signs put close to symbols also indicate the stimulus conditions; for example, r/g indicates the red direction for the central stimulus and green direction for the peripheral stimulus.

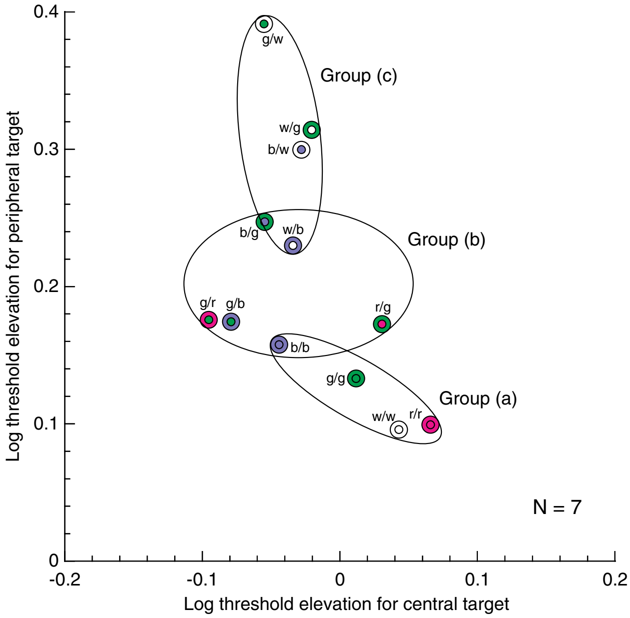

Fig. 5. Scattering diagram showing log threshold elevation for the peripheral stimulus plotted against that for the central stimulus. The inner and outer colors of each symbol indicate the central and peripheral stimulus colors. Group (a) the central and peripheral colors are the same. Group (b) the central and peripheral colors are different chromatic colors. Group (c) the central and peripheral colors are chromatic and achromatic colors.

It is shown in Fig. 5 that the log threshold elevations for the central stimuli disperse around 0 while those for the peripheral stimuli vary between 0.1 and 0.4. This indicates that the central task was not impaired, but the peripheral task was affected in the dual task condition, implying that the visual attention loads, which increased due to the dual task, affected almost exclusively the sensitivity for the peripheral stimuli.

It turned out that the threshold elevations for the peripheral stimuli depend on combinations of the central and peripheral color directions. We applied the one-way ANOVA to the three groups of (a), (b), and (c) to confirm significant effects of color combinations. The main effect of the color combination on the threshold elevation for the central stimuli was not significant $[F(2,9) = 2.770,\ p = 0.1155]$; that for the peripheral stimuli was significant $[F(2,9) = 16.357,\ p = 0.0010]$. The multiple comparison tests using Ryan's method $(\alpha = 0.05)$ showed that the threshold elevations for Group (c) were significantly different from those for the other groups. Therefore, there is a general tendency that the peripheral thresholds increase when a central and a peripheral stimulus have a chromatic–achromatic or an achromatic-chromatic combination. This tendency is partly inconsistent with the results of experiment 1 and 2 in which the peripheral threshold elevations were greater for chromatic responses than for achromatic responses, no matter which central task stimulus was achromatic or chromatic. It is likely that the pattern discrimination tasks employed in experiments 1 and 2 do not separately affect the achromatic and chromatic channel even if the stimulus pattern is made with either a chromatic or achromatic difference.

The results in experiment 3 are not consistent with the findings of Morrone *et al.* [6], which showed that the peripheral contrast thresholds did not increase when the central and peripheral stimuli were different in contrast modalities, chromatic or achromatic, whereas we found here that the peripheral contrast thresholds increased to the maximum degree when the central and peripheral stimuli were different in modalities. Saenz *et al.* [25,26] reported that performance on a dual task was significantly better when observers divided attention across two spatially separate stimuli sharing a common feature compared to opposing features. They employed red and green colors as stimulus features. Our results are consistent with the findings of Saenz *et al.*, since the log threshold elevations for red versus green combinations of the central and peripheral stimuli are higher than those for the red versus red and green versus green combinations, as shown in Fig. 5.

If chromatic and achromatic colors can be considered as different stimulus features of the same visual dimension, as in the case that red and green color threshold elevations for chromatic versus achromatic combinations in experiment 3 can be explained by the feature-based attention shown in Saenz *et al.*, but those in Morrone *et al.* cannot be explained. It was suggested in Morrone *et al.* that the chromatic and luminance differences were not different features in a visual dimension, but were assigned to different visual dimensions. It would be reasonable to take into account the possibility that visual features are task-dependent. In some visual tasks two visual attributes, such as chromaticness and achromaticness, might act as features of a visual dimension, but in other visual tasks they might be processed as different visual dimensions. Morrone *et al.* used a search task as their central task in which the observer judged whether the central stimulus included an odd target among other distractors. The odd target was either a white square in black distractors or a green square in red distractors. Although their targets were made with only luminance or chromatic differences, the observer did not have to direct attention specifically to a luminance or chromatic difference, but to something odd in a display. The peripheral task was not such a search task, but to discriminate the luminance or chromatic contrast between the left and right gratings to measure the increment thresholds. On the other hand, in experiment 3 as well as Saenz *et al.*, the observer performed the same task for two spatially separate stimuli. These two spatially separate stimuli had an identical stimulus configuration in Saenz *et al.* and were only different in size in experiment 3. It seems that in Morrone *et al.* experiments with chromatic and achromatic stimuli might not be processed in two different dimensions, whereas, in Saenz *et al.* and our experiments, chromatic and achromatic stimuli might be processed as two features in a single visual dimension.

6. GENERAL DISCUSSION

In experiment 1 we showed that when visual attention was primarily directed to central stimuli in the dual task, the increment spectral sensitivity measured for peripheral stimuli reduced to a greater degree for the short and long wavelengths than for middle wavelengths. This change in the spectral sensitivity function indicates less chromatic contributions than achromatic contributions to visual detection [15], suggesting two hypotheses for the effect of visual attention. The first hypothesis is that the chromatic system generally requires a greater amount of attention resources than the achromatic system, to detect stimuli. If not enough attention is paid to a stimulus, only the achromatic system can work to detect the stimulus. The second hypothesis is that, because the central stimuli are achromatic, the achromatic system is facilitated by attention in the whole visual field.

We found, in experiment 2, that the peripheral detection threshold obtained in the dual task, increased more for chromatic stimuli than for achromatic stimuli in a cone-opponent color space, and that the central stimulus color did not affect the detection thresholds of the peripheral stimulus. Experiment 2 rejected the second hypothesis, and supported the first hypothesis that greater attention is used for the chromatic system than for the achromatic system to detect a stimulus, at least in this task and stimulus condition. In experiment 3, we showed that the threshold elevations in the peripheral stimuli depended on the combination of the colors of the central and peripheral stimuli. The threshold elevations of the achromatic stimuli were not always smaller in the periphery than those of the chromatic stimuli, but larger when the central stimulus was chromatic.

It seems that we had inconsistent results in experiment 3 compared with those of experiment 2. This inconsistency might be due to the differences in the stimulus configuration and the visual task between the two experiments. We used the ring pattern for the central stimulus in experiment 2. The observer's task was to detect gaps in the rings drawn by the achromatic or chromatic lines. Even if the central stimuli were made in different way, the observer performed the same task. On the other hand, in experiment 3, the central stimulus was of eight disks, being the same as for the peripheral stimuli, and the central task was to detect the chromatic or achromatic difference. This stimulus configuration and the task would make the feature-based attention of color [27] be more effective in experiment 3. Thus, the difference of the central and peripheral stimuli in color conditions would be less sensitive in experiment 2 than in experiment 3, which might yield that the color combination of the central and peripheral stimuli has no effect in experiment 2, but significant effects in experiment 3.

All experiments here presented data that was inconsistent with those of Morrone *et al.* Their results showed the modality specificity of visual attention to luminance or chromatic dimension, that is, that the visual attention could interfere effectively only either in the achromatic or the chromatic channel. However, our results suggested that the visual attention could simultaneously affect the achromatic and the chromatic channel. This discrepancy in effects of the visual attention would be explained when we could carefully examine the stimulus and task conditions used in two studies. But the most important finding, consistent with previous studies, is that the visual attention selectively controls the responses in the chromatic and achromatic pathways, strongly suggesting that the visual attention affects functions in the early visual pathways.

In the present experiments, performances of detecting peripheral stimuli were compared for conditions in which either the peripheral stimulus was attended or the central stimuli received the highest priority of attention in a dual task condition. In the dual task conditions, observers responded first to the central stimulus, so they had to keep in mind the decision about the peripheral stimulus. There might be, therefore, a significant difference in the memory load for the two peripheral conditions. To test this possibility we carried out a supplementary experiment. The stimulus configuration and duration were the same as in experiment 3. The green and white color-directions were used for the central and peripheral stimuli, respectively. Both central and peripheral stimulus contrasts were set as eight times larger than the threshold contrasts to make stimuli clearly visible so that observers did not have to intensively pay attention to detect the stimuli. When the stimuli were presented, observers memorized spatial positions of the stimuli and then responded to the stimulus positions with a keyboard. A single task condition was also run, for both the central and peripheral stimuli. If observers were imposed on by a heavier memory load for the peripheral task in the dual task condition than in the single task condition, a significant difference would be obtained in the percentage of correct responses for the peripheral stimulus between the two task conditions. The same seven observers as in experiment 3 participated in this supplement experiment.

The results show that the average percentage of correct responses is 99.8% (central stimulus in single task), 100% (peripheral stimulus in single task), 99.8% (central stimulus in dual task) and 99.3% (peripheral stimulus in dual task). These percentages correct were not significantly different $[F(1,3) = 4.50,\ p = 0.0781]$. We can conclude that there is no memory effect on the measurement of thresholds in the present experiments.

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