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The effect of immediate background size on target detection

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Abstract
Several studies show that the surround conditions of an on-axis target have a significant effect on target visibility at the threshold between the target and the surround. In complex visual fields such as roadways in urban areas, where a target signal-to-noise ratio is often low, the surround conditions of targets may significantly impair a driver's ability to detect the targets.

This study investigated how the immediate background size of an off-axis target influences a driver's detection of the target at a mesopic light level under different conditions. The experiment used a target (subtended 2°×2°) framed by a square-shaped immediate background surrounding the target, and framed by a larger square-shaped far background surrounding the immediate background. The experiment varied the luminance contrast of the target to the immediate background and the size of the immediate background, but kept the luminance of the far background constant at 0.009cd/m^2. The target was located at 15° off-axis and was presented to six subjects under each condition. The reaction times and number of missed trials of detecting targets were measured to evaluate the subjects' ability to detect a change in the luminance contrast. The results suggested that, if the width of the immediate background framing the target was narrower than the size of the target (2 °), the immediate background impaired the subjects' peripheral detection of targets at the threshold. When the width of the immediate background was wider than that of the target, the reaction time was constant regardless of the width of the immediate background. As these results show, conventional luminance contrast of a target to its background cannot take into account the spatial effect of a complex luminance distribution around a target on the detection of the target. To quantitatively investigate how the immediate background influences the target detection, this study attempted to adopt an image filtering method that can analyze how strong and how frequent luminance changes exist over a specific area and its surrounds (Nakamura, 2000). The results of the analysis suggested that this image filtering method could explain the mechanism of target detection under complex background conditions.

1. Introduction

The visibility of a target is influenced by visual factors surrounding the target. To simplify conditions for these visual factors, most studies on target visibility assumed that the background of a target had uniform luminance distribution. However, in the real world, the backgrounds of actual targets have a more complicated luminance distribution. To take into account such complex background conditions, several studies divided a target's background into two areas—an immediate background and a far background—and investigated how these backgrounds affected target detection (see Goodspeed and Rea[3] for thorough review of relevant studies).

For instance, Lythgoe[1] employed Landolt rings on these two backgrounds for visual acuity tests. Lythgoe showed that as the immediate background luminance increased, acuity also increased as long as the immediate background luminance was nearly identical to the far background luminance. However, when the far background was darker than the immediate background, acuity quickly plateaued. As the immediate background luminance became closer to the far background luminance, the acuity plateau shifted higher. McCann and Hall[2] used one-cycle sine wave gratings as targets and showed that contrast sensitivity was also affected by surround luminance. They showed that contrast sensitivity was best in a large, uniform background where luminance was equal to the mean luminance of the grating. If the immediate background was small, as Lythgoe showed for acuity, lower immediate background luminance could reduce contrast sensitivity. If the spatial extent of an immediate background was greater than or equal to the wavelength of the target sine wave, the immediate background did not affect contrast sensitivity. Goodspeed and Rea[3] showed that, using response times for correct readings of four Landolt ring orientations, far background luminance influenced acuity only when the target contrast was near threshold and the size of the immediate background was nearly equal to the gap size of Landolt rings. These findings show that target visibility at threshold is significantly affected by the spatial extent and luminance of the surround field, especially by the immediate background. Under such a complex condition where a target is surrounded by both an immediate and a far background, especially when the size of the immediate background is relatively small, two contrasts should be taken into account: the contrast between the target and the immediate background, and, the contrast between the target and the far background.

Although these studies focused on on-axis targets, off-axis targets might be similarly influenced by the immediate background; the immediate background might significantly impair a driver's off-axis target detection at threshold. Since, however, a study on the contrast sensitivity function showed that the sensitivity to high frequency luminance modulations decreased as the eccentricity angle of the luminance modulations from the foveal vision increased[4], such angle-dependent characteristics of the contrast sensitivity may result in a somewhat different tendency for off-axis targets. To maintain better visibility in the peripheral visual field for safer driving, it is very important to investigate the effects of the immediate background on off-axis target visibility. In this study, a controlled laboratory experiment was conducted using a square target surrounded by the immediate and far backgrounds to investigate whether the immediate background of an off-axis target influences the off-axis target detection, and if so, how the immediate background impairs the subjects' target detection.

With regard to the analysis of the experimental results, the contrast between the target and the immediate background and the contrast between the target and the far background should be taken into account. The intensity of the two contrasts as well as the spatial relationships between the two backgrounds and the target may influence the target's visibility. The target framed by both the immediate background and the far background may complicate the interaction between excitation and inhibition in the receptive field. To analyze the effects of the spatial relationship and the luminance contrast between the target and its backgrounds on target detection, a method developed by Nakamura[4] was adopted. This method, based on an image filtering technique proposed by Nakamura and Inui[5], can indicate a "contrast" profile that illustrates how strong and how frequent luminance changes (waves) exist over a specific area and its surroundings (see Section 3. Discussion).

2. Experiments

2.1. Apparatus

This experiment took place in a laboratory where all interior elements, the ceiling, walls, and floor, were painted black. Figure 1 shows an experimental setup employed in this experiment. The setup was composed of a detection target, a micro-controller, a computer, a manual switch, a numerical signboard, and a flood lighting luminaire with a high-pressure sodium lamp (HPS). Each subject was asked to detect a change of reflectance of the detection target while fixating on the numerical signboard located at the center of the visual field. The detection target was located 15 degrees off-axis to the right when a subject looked straight ahead.

Figure 2 shows the detection target and its background conditions. The detection target was a liquid crystal (LC) panel covered by a 50×50 cm black board with a 10×10 cm opening in the center. The black board provided the far background as shown in Figure 2. Through the opening of the black board, each subject saw the surface of the LC panel that subtended 2°×2 ° for the subject position. The LC panel was electrically switched from transparent ($\rho \approx 0$ %) to frosted ($\rho \approx 20$ %). Changing the transmittance took approximately 250 milliseconds but this period was constant. A thin wood frame surrounded the opening and provided the immediate background for the target. By changing the frame, the size and reflectance of the immediate background were changed. When the LC panel turned transparent, the subject saw a board behind the LC panel. The same reflectance was used for the board and the frame; when the frame for the immediate background was changed, the board behind the LC panel was also changed. The computer controlled the detection target through the micro-controller. A resistive force sensor was used as a manual switch for a subject to signal target detection. The manual switch was attached to the desk surface in front of the subject. When the subject touched the sensor, the micro-controller measured the subject's reaction time from the time the target was activated until the subject touched the manual switch. The micro-controller sent the reaction time value to the computer that then recorded the reaction time, in milliseconds. The signboard, which was placed at a distance of 5 m from the subject, was composed of seven red LEDs and was controlled by another micro-controller. The signboard displayed a 30×20 cm (14×10 min of arc) numerical character for one second in a random order. Subjects were instructed to focus on the center of the signboard. Table 1 illustrates the details of the experimental system. A high-pressure sodium (HPS) luminaire behind the subject illuminated the black laboratory. A metallic mesh filtered the luminaire to reduce and adjust illuminance on the target.

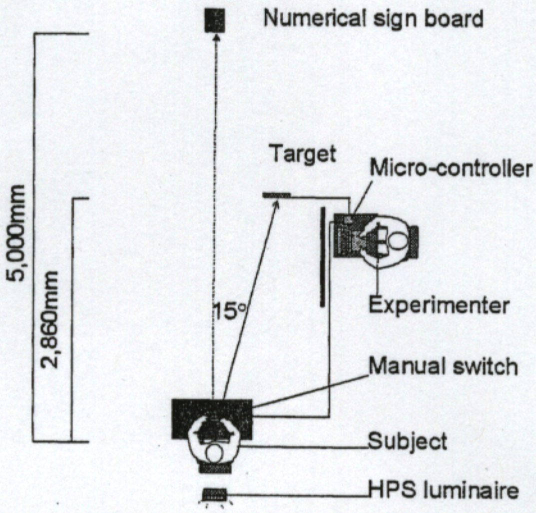


Figure 1. Experimental setup

Table 1. Experimental system

Description	Part name and number	Manufacturer
Liquid crystal panel	Privacy Glazing, Sample	3M
Micro controller	BASIC Stamp II Module, BS2-IC	Parallax
Computer	ChemBook 7200E, Intel Pentium III 600 MHz	ChemBook
Software	LabView 5.1	National Instruments

2.2. Experimental conditions

Table 2 summarizes the experimental conditions. In this paper, target, immediate background, far background, and background surround are defined as shown in Figure 2. Contrast* of the detection target against the immediate background and the size of the immediate background were changed. To change these variables, this experiment used nine different frames (three reflectance levels and three sizes) for the immediate background. For the condition at a contrast of 10, no frame was used for the immediate background. Under this condition, only the 50×50 cm black rectangular board ($\rho = 1$ %) surrounding the central 10×10 cm LC panel appeared to the subject. Through the experiment, the target reflectance and the far background reflectance were kept constant. Since light output of the luminaire was constant at an illuminance of about 1.5 lux on the target surface, the luminances of the target, far background, and background surround were constant at luminances of 0.100, 0.009, and 0.007 cd/m^2, respectively. Table 3 summarizes the measured luminances of the target and backgrounds. The experiment employed one SPD condition (HPS lamp) and a single target location (15 ° off-axis). Each experimental condition was repeated ten times for each subject.

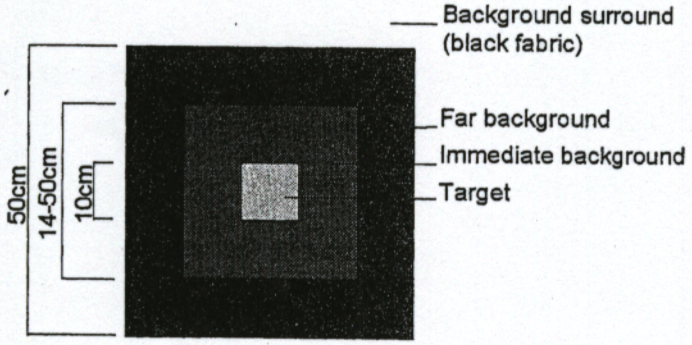


Figure 2. Definition of background

* In this section, contrast is defined as $(L_T - L_B) / L_B$.

Table 2. Experimental conditions employed in the forward headlight study

Variables	Ranges
Contrast of target against immediate surround* (cd/m^2)	0.42, 0.79, 2.2, (10**)
Size of immediate surround (degrees)	2.7, 5.8, 9.7

*The contrast conditions, 0.42, 0.79, and 2.2, corresponds to the immediate background reflectance levels, 18%, 12%, and 5%, respectively.
**The condition of a contrast of 10 did not use any immediate backgrounds. Under this no-frame condition, there was only a contrast between the target and the far background.

Table 3. Luminance of target, immediate background, far background, and background surround

	R1 (18 %)	R2 (12 %)	R3 (5 %)	No frame* (1 %)
Target (frosted)	0.109	0.100	0.109	0.100
Target (transparent)*	0.075	0.054	0.036	0.012
Immediate background	0.077	0.056	0.034	0.009
Far background	0.008	0.008	0.009	0.009
Background surround	0.007	0.006	0.007	0.007
Contrast—target (frosted) vs. immediate surround**	0.42	0.79	2.2	10

*When the target was transparent, subjects saw a board, behind the liquid crystal panel, whose reflectance was the same as the reflectance of the immediate surround.
** These contrasts correspond to those in Table 2.

2.3. Procedure

Six subjects (five males and one female) aging between 22 and 44 years old participated in the experiment. The subjects had normal color vision and corrected visual acuity. The presentation order of the immediate background sizes was counterbalanced across subjects. The presentation orders of the reflectance conditions were randomized. The no-frame condition (contrast = 10), which used no immediate background frame, was presented 10 times with each of the three immediate background sizes to check the consistency of subject performance over the experiment. Therefore, the presentation of this no-frame condition was repeated 30 times in total for each subject. Every subject completed 132 trials for the experimental conditions (9 experimental conditions ×10 repetitions + 30 repetitions for no-frame condition + 12 dummy presentations). In this experiment, none of the subjects had false positives.

In the experiment, an experimenter operated the computer-controlled system, issued instructions to the subject, and recorded the subject's responses and behaviors. After at least ten minutes practice, the subject started the 132 trials. The subject was required to detect a change of reflectance of the detection target while looking at and reading the signboard in front of the subject. The computer monitored and recorded the reaction times of the subject for each target presentation. The target was presented for two seconds. The interval of the target presentation was randomized between 10 and 15 seconds. The whole procedure took each subject about 30 minutes.

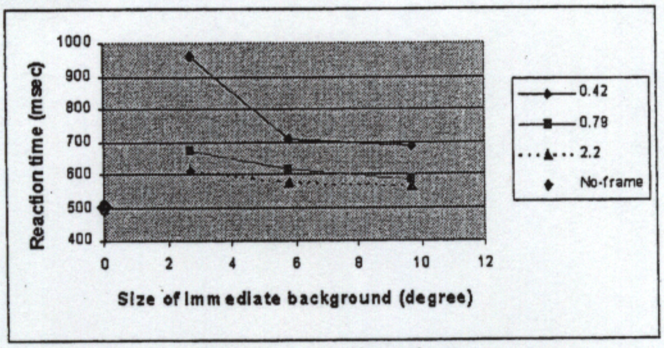
2.4. Results

The mean values of reaction times for each of the 10 experimental conditions were calculated for each subject. Then, the average of the mean values were obtained for each condition. Missed trials for each condition were counted for each subject and an averaged missed-trial number was calculated across subjects for each condition. Figures 3 (a) and (b) show the average of mean values, and average of missed-trial numbers per 10 presentations for all of the eight subjects for all of the 10 experimental conditions. The results of the no-frame condition are shown at the immediate background size of 0 degree. The results show the shortest reaction time and the smallest missed trial number for the no-frame condition.

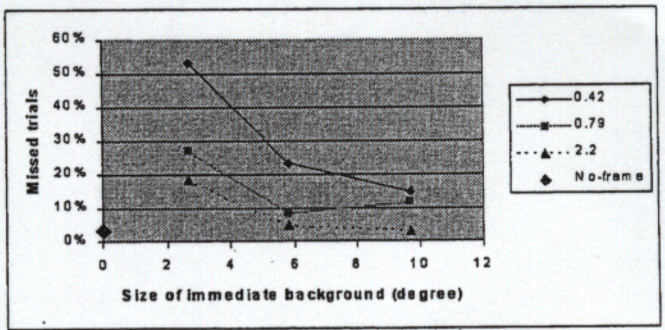
Figures 3 (a) and (b) suggest:

(1) The higher the contrast of a target to the immediate background, the shorter the reaction time, and the smaller the missed-target number.
(2) As the target contrast to the immediate background became higher (the target became easier to find), the influence of the immediate background size on target detection became smaller.

(3) For low contrast targets, as the size of immediate background became smaller, especially less than 5.8 ° (when the target width approximately equals to the frame width of the immediate background), the influences of the immediate background on target detection increased.



(a) Mean reaction time



(b) Mean missed trials

Figures 3. (a) and (b) Results of experiment

Two-way analyses of variance (ANOVA) were conducted using the results of reaction times and missed trials for nine (3 reflectances × 3 sizes) conditions, excluding the results of the no-frame conditions (contrast = 10). Tables 4 (a) and 4 (b) show the results of the ANOVAs. The results of the ANOVAs suggested that there was a significant difference in reaction times and missed trials between the different reflectance and size conditions for the immediate background. These results supported all of the three suggestions listed above. These suggestions, although they were obtained from off-axis targets, were consistent to the results of existing experiments on on-axis target detection[2, 3].

Table 4. (a) Two-way ANOVA for mean of reaction times

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Reflectance	452788.8	2	226394.4	6.898272	0.002437**	3.20432
Size	225076.3	2	112538.2	3.429055	0.041106*	3.20432
Interaction	117600.8	4	29400.2	0.895829	0.474376	2.578737
Within	1476855	45	32819			
Total	2272321	53				

*: p<0.05, **: p<0.01

Table 4. (b) Two-way ANOVA for mean of missed trials

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Reflectance	36.11111	2	18.05556	7.762739	0.00127**	3.20432
Size	56.33333	2	28.16667	12.10987	0.00006**	3.20432
Interaction	12.88889	4	3.222222	1.38535	0.254192	2.578737
Within	104.6667	45	2.325926			
Total	210	53				

**: p<0.01

3. Discussion

3.1. N-filtering and "contrast" profiles

To quantitatively analyze the effect of the immediate background on target detection, further analysis employed an image processing method to detect luminance changes proposed by Nakamura[5]. This method is a two-dimensional wavelet analysis using a set of image processing filters called N-filters[6]. Equations (1) and (2) represent the N-filters in the frequency domain and in the spatial domain, respectively. The N-filters are slightly modified second derivatives of Gaussians. The objective of the modification is to allow a luminance wave to pass through one of the N-filters without changing the intensity, or the amplitude, of the luminance wave if the wave has the same frequency as the N-filter. While passing through the original second derivatives of Gaussians, the wave amplitude is somewhat changed. The modification allows representing the intensity (amplitude) of a luminance change by a "contrast" of the center to the surround for each detection frequency, while the filtering is performed over a luminance image in logarithm unit. The second derivatives of Gaussians are the filters that Marr used to detect zero crossings[7] and are ideal band-pass filters in the shape of Mexican hats. It is believed that this Mexican-hat-shaped distribution represents the spatial organization of the retinal ganglion cells that is circularly symmetric, with a central excitatory region and an inhibitory surround[8]. Therefore, it is reasonable to apply the N-filtering, which is functionally identical to the second derivatives of Gaussians, to analyze interaction between two neighboring areas, i.e., a target and an immediate background.

$$\tilde{N}(u,v) = \frac{(u^2+v^2)}{f_0^2}\exp(1-\frac{(u^2+v^2)}{f_0^2}) \tag{1}$$

$$N(x,y) = \pi^3 f_0^4\left[\frac{1}{\pi^2 f_0^2} - \left(x^2+y^2\right)\right]\exp\left[1-\pi^2 f_0^2\left(x^2+y^2\right)\right] \tag{2}$$

where f_0: detection frequency [cycle/deg]
u: horizontal spatial frequency [cycle/deg]
v: vertical spatial frequency [cycle/deg]
x: horizontal position [deg]
y: vertical position [deg]

To analyze a luminance image using the proposed method, the luminance image should first be N-filtered. Practically, for a pixel *(m, n)* in a discretely recorded digital image *I (m, n)*, a set of N-filters, which are also discretely expressed in the spatial domain with narrow detection frequency ranges, are convolved over the image *I (m, n)* centered the pixel *(m, n)*. In this convolution process, luminances of pixels centered at the point are weighted by the discrete N-filters for every frequency, then, the weighted luminances are summed up, as Equation (3) shows.

$$I'(m,n) = \sum_k \sum_l I(m-k, n-l) \bullet N(k,l) \tag{3}$$

where I: discrete luminance image
I': discrete filtered luminance image
N: discrete N-filter expressed in spatial domain

Table 5 shows an example of the discrete N-filters when a sampling interval is 3.33 times of a detection frequency. This multiplier of the detection frequency is decided based on the sampling theorem according to precision needed in calculation. Summing up the weighted logarithmic luminances of all pixels overlaid by one (for a detection wavelength) of the N-filters, e.g., the matrix in Table 5, provides a luminance "contrast"[†] between the central area and the surround for each detection wavelength.

[†] This paper use both contrast and "contrast". The contrast is defined as $(L_T - L_B) / L_B$, where L_T is target luminance and L_B is background luminance. The "contrast" is luminance ratio of N-filtered luminance of a target to N-filtered luminance of the background. In a sense, the "contrast" can be defined as perceived contrast.

Table 5. A matrix of discrete N-filter

-0.000024	-0.000224	-0.001724	-0.003224	-0.001724	-0.000224	-0.000024
-0.000224	-0.006324	-0.035324	-0.056324	-0.035324	-0.006324	-0.000224
-0.001724	-0.035024	-0.065524	0.062476	-0.065524	-0.035024	-0.001724
-0.003224	-0.056324	0.062476	0.572752	0.062476	-0.056324	-0.003224
-0.001724	-0.035024	-0.065524	0.062476	-0.065524	-0.035024	-0.001724
-0.000224	-0.006324	-0.035324	-0.056324	-0.035324	-0.006324	-0.000224
-0.000024	-0.000224	-0.001724	-0.003224	-0.001724	-0.000224	-0.000024

Figure 4 illustrates a simplified example of procedure for the N-filtering over for a target and its uniform background. Figure 4 also shows three one-dimensional N-filter functions for short, medium, and long detection wavelengths (actual N-filters are two-dimensional functions). Since calculation over the whole image is time-consuming, this paper conducts calculation only for the central point *(m, n)* of the target so as to represent the whole image and simplify the calculation procedure.

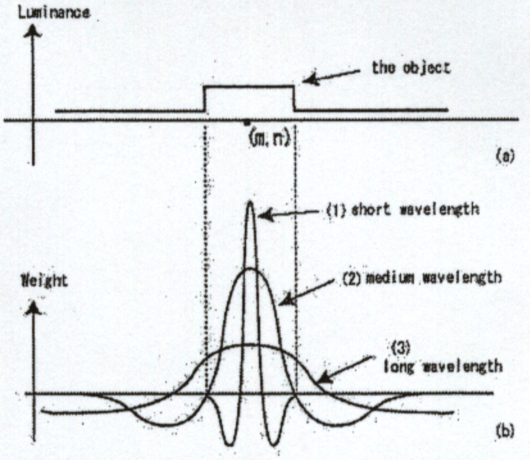


Figure 4. Relation between size of the object and detection wavelength

By conducting the calculation using various detection wavelengths, a series of luminance "contrasts", i.e., the perceived luminance ratios between the target and the background over the wide range of wavelengths, can be obtained. The series of "contrasts" compose a "contrast" profile, as shown in Figure 5. The "contrast" profile illustrates how strong "contrast" exists between the target and the background with regard to each detection wavelength. The horizontal axis in this figure indicates detection wavelength in degree and the vertical axis indicates the "contrast" of the filtered luminance image.

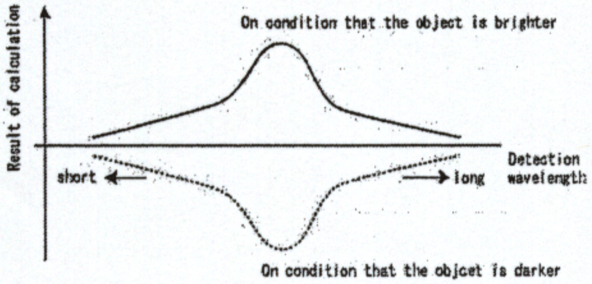


Figure 5. Contrast profile

As increasing the detection wavelength from short to long, the "contrast" between the center and the surround increases until it reaches Lt/Lb (Lt: target luminance, Lb: background luminance), where the wavelength corresponds to $d \times \pi/2$ (d: diameter of the object). This "contrast" is called the prime "contrast." Then, a further increase of detection wavelength results in a decrease of the luminance ratio to 1, namely, 0 in a logarithmic scale.

It is also believed that human vision has multiple channels that respond to narrow ranges of spatial frequency and compose the contrast sensitivity function of human vision[9]. Therefore, the N-filtering, which analyzes the "contrasts" of the target and the background in filtered images for individual multiple detection wavelengths, is a reasonable approach to the mechanism of target detection under complex background conditions. This method may lead to a good explanation for how the immediate background conditions affected the results of the target detection.

3.2. "Contrast" profiles under experimental conditions

The N-filtering examined the luminance distributions around the target under all the experimental conditions. Figures 6, 7, and 8 show the "contrast" profiles for the central point of the target when the immediate background sizes are 2.7, 5.8, and 9.7 respectively. To maximize the precision of calculation, this analysis used an infinitely large matrix as the N-filters. In these figures, solid lines illustrate the "contrast" profile for the frosted targets and dotted ones are for the transparent targets.

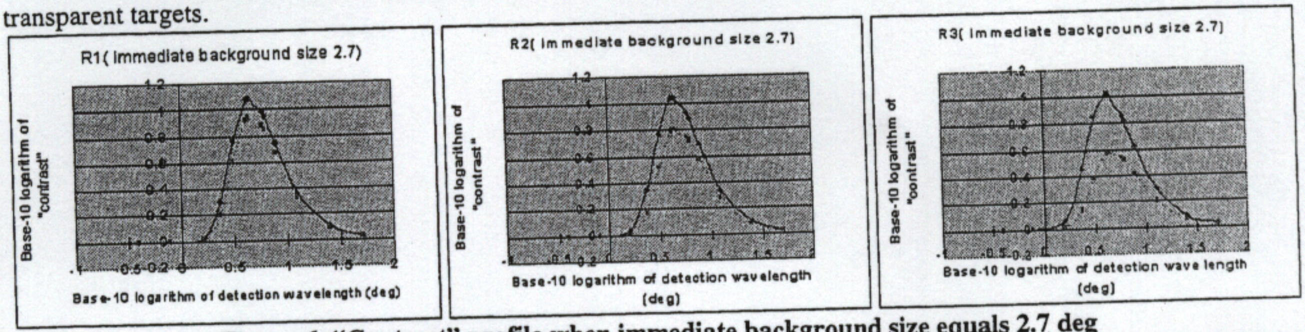


Figure 6. "Contrast" profile when immediate background size equals 2.7 deg

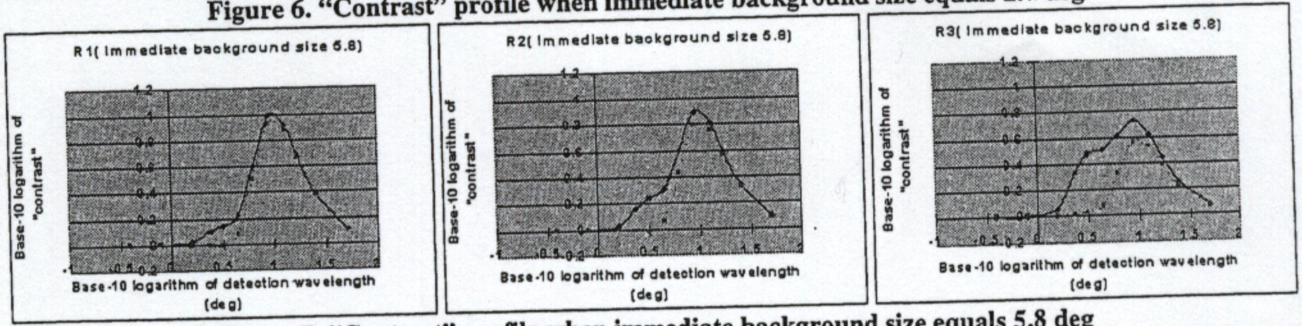


Figure 7. "Contrast" profile when immediate background size equals 5.8 deg

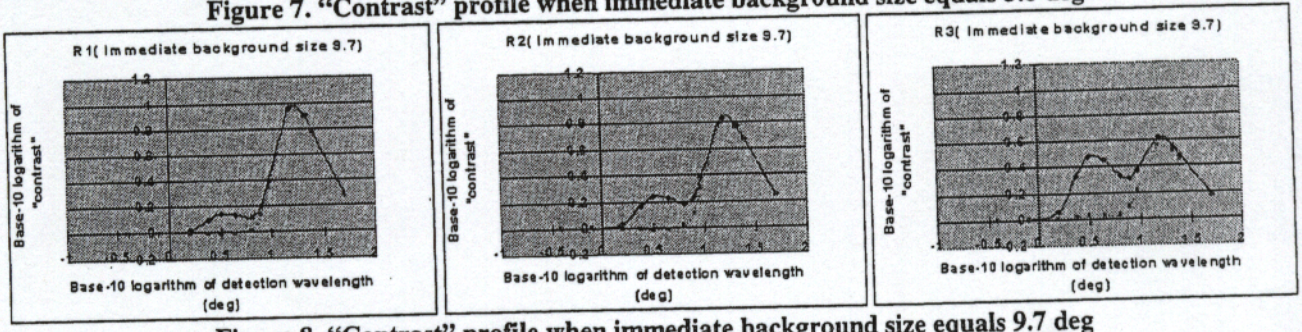


Figure 8. "Contrast" profile when immediate background size equals 9.7 deg

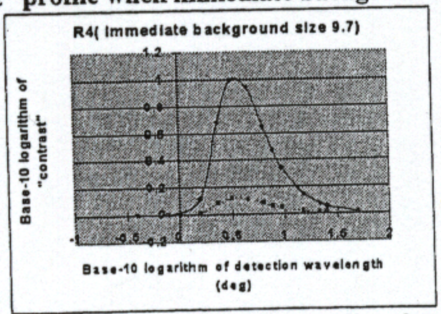


Figure 9. "Contrast" profile for no-frame immediate background condition

Under all the conditions, even when the LC panel for the target was transparent, strong luminance "contrasts" were obtained because the luminance "contrasts" between the immediate background and the far background always existed. These "contrast" values were nearly equal to the luminance ratios of the immediate background to the far background. A slight difference occurred because the target was not circular but square. The peak "contrasts" were obtained when detection wavelength was nearly 4.24 ° (0.63 in logarithm) for the immediate background size 2.7 °, nearly 9.11 ° (0.96 in logarithm) for the immediate background size 5.8 °, and nearly 15.2 ° (1.18 in logarithm) for the immediate background size 9.7 °. These "contrast" peaks do not correspond to the peaks of the prime "contrast" made by this 2°-diameter target. For this target, the prime "contrast," where the target appears most distinct against the background, should appear at around 3.14 ° in wavelength ($2 \times \pi/2 = 3.14$), or at 0.49 in logarithmic wavelength.

3.3. Relationship between reaction time and "contrast" profile

It is reasonable to think that the target detectability rises as the difference in "contrast" between the transparent target and the frosted target increases. In Figure 6, with the immediate background size 2.7 °, the difference in "contrast" profile between the transparent target and the frosted target appears smaller than the other immediate background sizes for all the reflectance conditions. This occurred because the "contrast" of the target to the immediate background principally appeared in the same wavelength as the "contrast" of the immediate background to the far background. It is well known that the increment threshold value of a target against its background increases as the luminance of the background increases because the contrast threshold ($\Delta L/L$) is constant (Weber's law). Since, under the 2.7 ° conditions, the "contrast" increases, caused by the target, overlapped the " contrast" peak of the immediate background against the far background, the subjects might have had difficulty in detecting the "contrast" increases.

If Figures 3 (a) and (b) are compared with Figures 6, 7, and 8, it is obvious that the larger the difference in "contrast" between the transparent target and the frosted target becomes, the shorter the reaction time becomes. To represent the difference in "contrast" over the profile, it was assumed that the difference could be represented by summing the differences of the luminance "contrasts" powered by 0.33. The exponent 0.33 was tentatively used to represent the above-mentioned non-linearity of the visual system. Figure 9 shows the relationship between the reaction time and the difference in "contrast" between the two profiles. Figure 9 shows a simple linear relation between the contrast difference and the subject reaction time. Figure 9 also suggests that we may easily detect the luminance change (wave) of the target when the difference in "contrast" profile increases. In reality, the contribution of the intensity of luminance wave should differ in wavelength because the visual system has a contrast sensitivity function. Since few studies investigated the contrast sensitivity to off-axis modulation stimuli, especially in the low frequency region, this study did not attempt any sensitivity corrections. However, for instance, a modulation sensitivity function to a 16° off-axis stimulus shows that the sensitivity decreases as the spatial frequency reduces from 3 cycles per degree to 1 cycle per digree[4]. If this tendency can be extrapolated to the lower spatial frequency (longer wavelength) region, the lower frequency wave in the experimental conditions may have less influence on target detection. Further analysis of contrast sensitivity may provide a better correlation coefficient value. Further studies using more conditions and subjects are needed.

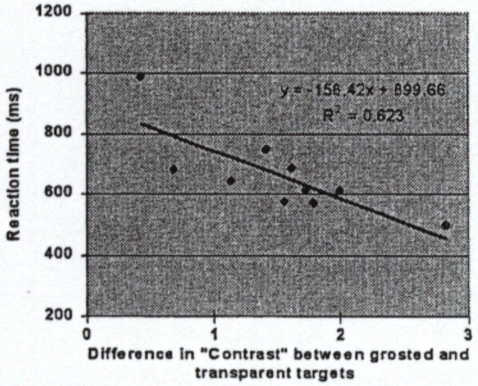


Figure 10. Relationship between reaction time and "contrast" difference between transparent and frosted

4. Conclusion

This study conducted an experiment using an off-axis target under different background conditions. The study suggested that, under these experimental conditions, if the frame width of the immediate background surrounding the target was narrower than the size of the target (2 °), the immediate background impaired subjects' peripheral detection of targets at the threshold. When the width of the immediate background was wider than that of the target, the reaction time was constant regardless of the width of the immediate background. Further, an image filtering method proposed by Nakamura was applied to the results of the experiment. The results of the experiment suggested that the spatial extent and luminance of immediate background significantly affected off-axis target detection. This tendency was consistent to the results of existing experiments on on-axis target detection. The results of the N-filtering analysis suggested that the difference in shape of the "contrast" profile might be able to explain this phenomenon.

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