The significance of surround conditions for roadway signs

Charles H. Goodspeed IV and Mark S. Rea, Ph.D
Lighting Research Center, Rensselaer Polytechnic Institute
Troy, NY 12180

1996 IESNA Annual Conference, Cleveland, OH, USA
24-May-1996

INTRODUCTION

The visibility of a target not only depends upon its size, contrast and background luminance, but upon visual factors surrounding the target background (Figure 1). Lythgoe (1932), for example showed that visual acuity was affected by the luminance of the area surrounding the target background. He showed that surrounds darker than the target background reduced acuity. Naturally, one might expect other spatial, chromatic, and temporal factors in the surround to influence target visibility.

Presently, no model (e.g., Rea and Ouellette, 1991) explicitly considers the impact of surround conditions on target visibility. The purpose of this study was to begin to understand the impact of surround conditions on traffic sign visibility. The approach taken was to create a controlled, laboratory situation where some key factors affecting sign visibility might be studied. Three independent variables, target contrast, border width and surround field luminance, were used to assess sign visibility, operationally defined by two dependent variables, response times and subjective judgements of readability. It was hoped that this laboratory approach, together with a review of the literature, would identify important principles that could be used to guide traffic sign design and maintenance.

BACKGROUND

Several studies have been conducted under threshold conditions looking at the impact of surround conditions on visibility. Lythgoe (1932) showed that acuity, using minimally resolvable Landolt ring gap orientations, was affected by the luminance of the immediate background for the target as well as the luminance of the field surrounding the target background. As target background luminance increased, so did acuity as long as the ratio of the surround luminance to the background luminance was equal to one. When the ratio of the surround luminance to the background luminance was less than one, acuity reached a plateau; further increases in background luminance did not improve acuity. The closer the ratio of the surround luminance to the background luminance was to one, the higher the acuity plateau.

McCann and Hall (1980) showed that contrast sensitivity, using one-cycle sine wave gratings, was also affected by surround luminance. They showed that contrast sensitivity was best in a large, uniform surround field whose luminance was equal to the mean luminance of the grating. If the surround field was quite small, then, like Lythgoe showed for acuity, lower surround luminance reduced contrast sensitivity. As long as the grating was flanked by a surround field whose spatial extent was greater than or equal to the spatial frequency of the sine wave target, however, contrast sensitivity was not affected. These findings show that target visibility at threshold is significantly affected by the spatial extent and the luminance of the surround field at threshold.

Under suprathreshold conditions, Rea, Ouellette, and Tiller (1990) measured response times and subjective judgements of visibility using a numerical verification task. Two lists of numerals were flanked by surrounds of different reflectance and spatial extent. Surround conditions had no significant effect on reading speed nor on subjective judgements of visibility in their experiment. Mace, King, and Dauber (1985) presented traffic signs within spatially complex fields and obtained subjective judgements of visibility. Again, under these suprathreshold conditions, traffic sign visibility was not affected by surround conditions.

Collectively these studies show that surround conditions have an effect on visibility, only at the break point between seeing the target and not seeing the target (i.e., at threshold). When the target is well above threshold, surround conditions have no effect. In general then, it can be inferred that when the target signal to noise ratio is high (e.g., target contrast is high), surround conditions are not important and, conversely, when it is low (e.g., target contrast is very low), surround conditions (and probably many other factors) become significant for target visibility.

Finally, recent research suggests that different measures of visibility produce different response functions. Ingling and Martinez (1983) described two classes of psychophysical responses to flashed targets. Two target flash durations were tested, 4 ms and 300 ms. Dimming the intensity of the shorter flash had little effect on subjective judgements of brightness, until a final small adjustment of intensity made a bright flash suddenly disappear. Dimming the 300 ms flash produced corresponding gradual reductions in subjective judgements of brightness until it finally disappeared. Consistent with Ingling's (1977) earlier discussion, they concluded that subjective judgements of brightness to the very brief flash were dependent upon the phasic (Y) channel which responds like an on/off switch, while the tonic (X) channel, which produces a graded response, determined subjective judgements to the longer flash.

Using micro-electrodes, Kaplan and Shapely (1986) observed responses from two classes of retinal ganglion cells (in macaque monkeys) to flashed targets of different contrast. These, so called alpha and beta cells are linked to the magnocellular layers and the parvocellular layers of the lateral geniculate nucleus (LGN) of the brain, respectively. In response to the same visual target, the alpha cells displayed a nonlinear, on/off response characteristic but the beta cells displayed a much more linear response characteristic. Figure 2 illustrates the nearly linear nature of the parvocellular response amplitude and the on/off nature of the magnocellular response amplitude to target contrast.

These studies suggest that the human visual system has at least two response channels and that for a given visual target, the results of an experiment can differ depending upon the response requested of the subjects. Following Rea (1989) it is hypothesized that response times are based upon the phasic (magnocellular) response channel, but subjective judgements to the *same* target steadily viewed (300 ms or longer, following Ingling and Martinez [1983]) will be based upon the tonic (parvocellular) response channel.

METHODS

Subjects

Two fifty-year old female subjects participated in the experiment. Both subjects had uncorrected 20/20 vision, as measured by a Bausch & Lomb Orthorator. They were determined to be color normal using American Optics isochromatic color plates. The subjects held valid driver licenses, and periodically participate in experiments conducted at the Federal Highway Administration's Turner Fairbank Highway Research Center, located in McLean, VA, where this experiment took place. Both subjects were paid a set fee for completing the entire experiment. One subject was run at a time.

Apparatus

Figure 3 illustrates the experimental set-up to obtain the response times required for a subject to quickly identify the gap orientations of four, suddenly presented Landolt rings and to record subjective judgements of visibility of the same Landolt rings steadily with no time limitation.

Subjects viewed the visual task monocularly through circular artificial pupil, 0.04 in. (3 mm) in diameter, while comfortably seated in a chair and their chin positioned in a rest. A mirror was located 10 ft (3.0 m) from the artificial pupil and 10 ft (3.0 m) from the visual task. Ten feet (3.0 m) behind the mirror plane, a rear projection screen supplied the surround field conditions. The artificial pupil and chin rest properly aligned the subject with the target and the surround field so that the target and the background were seen in the same visual plane, 20 ft (6.0 m) away.

The visual target consisted of a two-by-two array of Landolt rings. The rings were cut from white vinyl and fixed in the center of a 15 by 15 in. (0.375 by 0.375 m) transparent glass panel. Four rings were fixed on each of three glass panels; the orientations of the rings was randomly determined. The four rings on each glass panel were separated at the narrowest point by a distance equal to the width and height of a ring gap (Figure 4). The lateral (and vertical) visual angle subtended by a ring gap, viewed at the 20 ft (6.0 m) viewing distance, was 2.75 minutes of arc. In terms of spatial frequency, the gap width (or height) is assumed to be approximately half its fundamental frequency of 10.9 cycles per degree. The solid angle of the square gap was 4.9×10^{-7} steradians. This gap size was chosen to simulate the critical detail of the text of a typical highway sign viewed at 200 ft (Paniati and Mace, 1993).

The contrast of the Landolt rings was varied by a combination of front and back lighting. A glass panel with four Landolt rings was placed in front of a translucent rear projection screen (Figure 3). A standard illuminant A light source (CCT = 2875 K), located behind the translucent screen produced a uniform background on which the Landolt rings could be displayed in silhouette. Fluorescent lamps (Philips

F32T8/TL835) mounted on the front side of the target window wall illuminated the Landolt rings. Without the front illumination subjects saw a uniform white field with four dark Landolt rings located in the center of the visual field. Landolt ring contrast was decreased by increasing the amount of light on the front surface of the glass panel. A four position switch wired to an electronic dimming ballast that adjusted the illuminance on the Landolt ring such that contrasts of 0.2, 0.4, 0.6, and 0.8 were produced. Contrast was defined as $(L_b - L_t)/L_b$, where L_t and L_b are the luminances of the Landolt rings and their immediate background, respectively. A target background luminance of 7 cd/m^2 ± 0.2 cd/m^2 was maintained at every contrast setting.

Different surround field conditions were produced by changing the image on the rear projection screen and by changing the size of the mirror used to see the visual target. The surround field was square and 17 degrees on a side (Figure 4). A uniform field or a 30 by 30 grid of Landolt rings of the same size as the visual targets could be displayed on the rear projection screen. The Landolt rings in the grid had a contrast of 0.8 and, like the visual targets, were separated from each other by a distance equal to one ring gap (2.75 minutes of arc).

Neutral density filters (Kodak nd 2.0 through nd 0.1), ranging in transmittance from 0.01 to 0.79, were used to simulate four night-time driving light levels. The luminances of the uniform surround field were set at 0.03, 0.15, 0.3, and 3.0 cd/m^2. The average luminances of surround field containing the Landolt ring grid were 0.01, 0.05, 0.1, or 1.0 cd/m^2. The luminance values for the grid field were lower than the corresponding ones for the uniform field because the area of measurement included the Landolt rings as well as their immediate background.

Four different border widths were employed in the experiment. Three border widths were obtained by using three different mirror sizes (Figure 4); the smallest mirror produced the border width equal to one ring gap (2.75 minutes of arc). Another mirror produced a border width equal to the diameter of a Landolt ring (13.75 minutes of arc), and the largest mirror produced a border width 2.5 times the diameter of the Landolt ring (34.4 minutes of arc). The fourth border width condition was created by projecting the uniform field on the rear projection screen; the largest mirror was used for this condition.

A timed shutter system was used to measure response times on a given trial. A shutter covering the Landolt rings was held in place by a retractable pin. When the experimenter removed the pin, via a lever system, the shutter dropped and revealed the Landolt rings. An electronic timing circuit was simultaneously and automatically started. A hand-held button operated by the experimenter was released just after the subject orally reported the orientation of the fourth ring; this turned the electronic timing circuit off. The elapsed time, in seconds, was then displayed to the experimenter on an LED readout (with accuracy to 0.01 s) and recorded on paper. Timing accuracy by the experimenter was estimated to be ±0.1 s using a known time interval. The luminance of the shutter was 6.8 cd/m^2, slightly less than the background luminance for the Landolt rings.

The orientations of the Landolt rings were changed after every trial. The square glass panels with the Landolt rings were rotated successively to each of its four positions and then a different panel was put in place. It was assumed that this simple procedure minimized learning of gap orientations by the subjects.

Procedures

Before a subject began the day and to ensure that the fluorescent lamps were stabilized, all lamps were operated for a minimum of 30 minutes before target contrast and surround field settings were measured. Luminance measurements were obtained with a calibrated meter (LMT, model 1009).

A subject was brought into the darkened laboratory from an office environment and allowed to adapt for five minutes. While the subject was adapting the chin rest and chair were adjusted for accurate alignment. The subject was then given five practice response time trials. The subject had been told to read the orientation of the Landolt rings from left to right, beginning with the top row. The timer was stopped after the subject reported the orientation of the fourth Landolt ring. The response time was recorded by the experimenter. Following the practice trials the subject was asked if she was comfortable and ready to begin. Both subjects were ready for the experiment after five practice trials.

The experiment consisted of a 4 x 4 x 4 (contrast x border width x surround luminance) counterbalanced, within-subjects design. One sub-block of 10 or 12 trials was associated with each experimental condition for each subject. A sub-block usually consisted of 10 errorless trials. Two additional trials were run if the subject did not accurately report one or more gap orientations. If 12 trials were completed without recording ten errorless trials, then the times associated with those trials where three out of four Landolt ring orientations were correctly identified were used for subsequent data analysis. The experiment proceeded until a block of trials was completed; a block of trials consisted of one surround luminance, one border width, and all four target contrasts.

The experiment was completed in two days; half of the blocks were completed each day. During the experiment subjects were given ten-minute breaks approximately every 45 minutes; one hour was given for lunch. Subjects were allowed additional rests if they requested, and were told they could leave at any time. Both subjects completed the experiment with little difficulty. One subject returned for follow-up session to obtain additional subjective rating data.

In the follow-up session the subject was shown the narrow border width and lowest field luminance with the highest target contrast (i.e., 0.8). The subject was then told that the visual scene rated a subjective readability rating of "ten." The target contrast was then switched to each of the three remaining settings and, using the highest contrast as the reference, the subject rated, in turn, the readability of the remaining Landolt rings on a scale from one to ten. Every combination of field luminance and border width was presented with every target contrast in the same manner; the highest contrast was shown first, assigned a value of "ten" and then the readability of every other target contrast was rated by the subject on a scale from one to ten.

RESULTS

The data were analyzed statistically using multiple t-tests. Fifteen planned comparisons were established prior to data collection. Limiting the planned comparisons to this number reduces the likelihood of a type I error (McGuigan, 1993).[*] Tables 1 and 2 show the results of the planned comparisons for response times (two subjects) and subjective judgements of readability (one subject).

Figure 5 shows the effect of target contrast on response times. There was a significant difference between the response times at a contrast of 0.2 and all others, but not between response times associated with any of the other three target contrasts.

Figure 6 shows the impact of border width on response time. The narrowest border width was associated with significantly longer response times than the medium border width, but there was no difference between the medium and large border width.

Figures 7 and 8 show the interactions between border width and target contrast and between border width and field luminance, respectively. The details of the statistical comparisons are given in Table 1, but the results illustrated in both figures show, again, that narrow border width in combination with low contrast and with low field luminance significantly increases response times.

Figure 9 shows the interaction between field luminance and contrast. Surprisingly, there was a significant difference between response times at the lowest field luminance and highest field luminance for the highest contrast (0.8) but not between these same two field luminances at the lowest contrast (0.2). The variances in responses at the lowest contrast where much greater than those at the highest contrast, and no doubt this prevented the difference between these two means from reaching statistical significance. The differences between mean response times at the lowest and the highest field luminances for both target contrasts are not considered important; certainly these differences are quite small.

Figure 10 shows subjective judgements of readability as a function of target contrast. There was a significant difference between the ratings for every target contrast as shown in Table 2. No other planned comparisons reach statistical significance.

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[*] See Appendix for a discussion of limited, planned comparisons.

DISCUSSION

Surround conditions

McCann and Hall (1980) showed that contrast sensitivity was not affected if the target (a sine wave grating of one cycle) was flanked by a border equal to or larger in size than the fundamental spatial frequency of the target. The data obtained in this study support that conclusion. Figures 6 through 8 show that at a target contrast of 0.2 (i.e., near threshold) response times are significantly longer at the narrow border width (2.75 min of arc, or half the fundamental spatial frequency of the target, 10.9 cycles per degree) than they are for the other border widths (2.5 times the fundamental spatial frequency of the target and above). At target contrasts 0.4 or higher, surround conditions no longer affected response times. Surround conditions have no apparent impact on subjective judgements of target readability under any conditions.

Collectively then, these data suggest that surround conditions are important for response times at or near threshold but are unimportant under suprathreshold conditions. In other words, when the signal-to-noise ratio in the visual system is low (i.e., for visual targets near threshold), surround conditions are important to visual performance as measured in terms of response time; when the signal-to-noise ratio is high (i.e., for suprathreshold conditions) surround conditions are not important.

For roadway applications, this study suggests that surround conditions will only be important to sign visibility when the sign text approaches threshold conditions. For traffic sign design and maintenance it is therefore important to keep the size of the sign text large and the contrast high (0.4 or greater). Where this is not always possible (e.g., in poor atmospheric conditions) a border equal in size to the fundamental frequency of the target will optimize visibility; larger borders will not further improve text visibility. For example, if the lateral extent of the critical detail of the target was determined to be 2.5 minutes of arc, then, because the detail constitutes approximately half of the fundamental spatial frequency of the critical detail, a border width of 5 minutes of arc would be necessary to ensure maximum visibility. Finally, visual search was not a part of this study, so these conclusions are not necessarily true where the target location is unknown.

Model predictions

Presently no model of target visibility expressly accounts for surround conditions. As just discussed, surround conditions are only important to response times at or near threshold. Therefore, a model based upon response times, such as the one by Rea and Ouellette (1991), should predict these results under suprathreshold conditions but would not necessarily make accurate predictions at or near threshold.

Table 3 summarizes the experimental parameters used in this experiment and the comparable parameters used in obtaining predictions from the visual performance model by Rea and Ouellette (1991). It will be noted that the target size used in this study was smaller than the range covered in their visual performance model, so the smallest possible target size in the model was assumed in generating the predictions.

Response times reflect a combination of both visual and non-visual processing times. The non-visual factors contributing to response times will be different for different experimental paradigms, but the visual factors should be the same and should be predicted by the visual performance model. Two approaches can be taken to isolate the visual from the non-visual processing time. The first would be to obtain an estimate of the non-visual processing time and subtract that value from the response time. This is the approach taken in computing relative visual performance (RVP) in the visual performance model. Since RVP is a ratio of two visual times, an estimate of the non-visual response times must be obtained before computing the ratio. These estimates are difficult to make, and probably unnecessary in the second approach. The second approach is based upon an estimate of the incremental time necessary to process the visual stimulus, relative to the processing time required for a reference stimulus. Under the assumption that the non-visual factors were constant (on average) throughout the experiment, then the incremental visual response time, ΔT_{vis}, is an estimate of the relative increase (or decrease) in time necessary to process another visual stimulus. This latter approach was taken in comparing the data from this study to the visual performance model predictions by Rea and Ouellette (1991).

The data in Figure 5 collapsed across all border widths and surround field luminances were used to make the comparison. The average response time for the highest contrast (0.8) in Figure 5 was subtracted from the average response times associated with each of the four target contrasts to obtain four incremental response times. Since the visual performance model predicts the time to process a single stimulus, the incremental response time values from Figure 5 were divided by four because they were based upon subjects seeing four Landolt rings. The resultant incremental values are plotted in Figure 11 together with the ΔT_{vis} predictions from the visual performance model.

As expected, the visual performance model closely predicts the incremental times for suprathreshold conditions (above a contrast of 0.4) but the model cannot make accurate predictions of visual performance near threshold because the model does not expressly account for surround conditions.

Two points are worth making from this comparison, one practical and one theoretical. From a practical perspective one must wonder whether the resources necessary to obtain a model of visual performance near threshold could be better spent on other endeavors. At threshold *every* visual factor (color, size, contrast, surround clutter, visual field size, observer age, etc.) becomes important and these factors will no doubt interact with one another. Great effort and time would be required to develop a comprehensive and valid model of visual performance for threshold conditions. Since in roadway lighting one is primarily interested in *avoiding* threshold conditions, it seems of limited practical importance and quite expensive to develop a model of threshold visibility.

From a theoretical perspective, this comparison lends doubt to the validity of any model that would attempt to predict suprathreshold response from threshold data (e.g., CIE, 1981). Since threshold responses are so highly dependent upon the stimulus conditions, model predictions will be highly sensitive to slight changes in every possible visual factor and the interactions between them. Any uncertainty in the threshold data will be greatly magnified when extrapolating to suprathreshold conditions. Under suprathreshold conditions, where the signal-to-noise ratio is high, most of these visual factors become unimportant, and measurement uncertainty will not be amplified when predicting suprathreshold performance. Thus, a model of suprathreshold performance based upon suprathreshold data obviates the risk of using hypersensitive, threshold model extrapolations to suprathreshold conditions.

Visual channels

Response times (Figure 5) and subjective judgements of readability (Figure 10) follow different functions of target contrast. It is also true that those stimulus factors that affected response times in this experiment, (i.e., border width and surround field luminance) were not found to be important to subjective judgements. It should be pointed out, however, that comparisons between the two dependent variables are not strictly valid in this study because fewer subjective judgement data were obtained than response time data, and the paucity of the former data may have prevented finding statistical significance with stimulus factors other than target contrast. More data would have to be obtained to determine whether these other stimulus factors are important to subjective judgements. Again, it is nevertheless clear in comparing Figures 5 and 10 that response times and subjective judgements follow very different functions of target contrast.

Rea (1981, 1986) discussed the relationship between response times and errors. His earlier data (Rea, 1981) showed that time and errors (misses and false positives) follow similar if not identical functions. If one assumes that the amplitude of the electrical signal recorded from the LGN is roughly proportional to the reciprocal of errors (as well as response time) measured psychophysically, then comparisons can be made, albeit roughly, between the electrophysiological data found in Figure 2 from Kaplan and Shapely (1988) and the data in Figures 5 and 10 obtained here. The electrical response data from the parvocellular layer of the LGN in Figure 2 and the subjective judgement data in Figure 10 both increase nearly linearly with contrast. The electrical response data from the magnocellular layer follow a much more step-like function with contrast, like the data in Figure 5. (Of course one must consider the reciprocal of the response time data in Figure 5 in making this comparison.) These comparisons suggest then that the response time data in Figure 5 are based upon the magnocellular (or phasic) channel response whereas the subjective judgement data in Figure 10 are based upon the parvocellular (or tonic) channel response.

In designing traffic signs, it becomes important to decide which suprathreshold response is important. The more step-like magnocellular response, presumably leading to response times, would suggest a clear "knee" that could be used to set minimum standards for the contrast of text on a roadway sign. The more linear parvocellular response has no convenient "knee" and other criteria would have to be considered in setting minimum standards.

As a footnote of some importance for roadway lighting application committees who use visibility data in forming recommendations, the phasic and tonic responses functions cannot be deduced from threshold measurements because, presumably, they share the same threshold. Thus, any visibility model based on threshold data (e.g., CIE, 1981) cannot predict these two different suprathreshold responses except through post hoc analyses. In making recommendations for traffic sign design and maintenance, it is therefore important to consider which measure of visibility, response time or subjective judgements, forms the basis of those recommendations.

SUMMARY

There are three major conclusions from this study. First, surround conditions are unimportant to response times and to subjective judgements of readability of traffic signs as long as the target is well above threshold conditions. Second, the visual performance model by Rea and Ouellette (1991) seems to be accurate for predicting response times under a wide variety of suprathreshold conditions, but near threshold stimulus parameters not expressly covered in the model will lead to discrepancies between predictions and data. Third, visual responses can be obtained from two distinct channels, each having different response properties and each providing different insights into visibility.

APPENDIX

Discussion of limited, planned comparisons

The omnibus F-test, or ANOVA, typically used in inferential statistics is of limited utility. In multivariate parametric experimental designs incorporating several levels of the different independent variables, the omnibus F-test can only provide information about the likelihood that one or more level of the independent variable is different than the others. It cannot provide information as to which level or levels are different than the others. Consequently, *a posteriori*, or post hoc, statistical tests such as the Tukey, Scheffé or Bonferroni multiple comparison methods must be employed after performing the omnibus F-test to determine which levels of the independent variable are statistically different (Myers, 1972).

Another approach to the problem of ascertaining which levels of the independent variables are statistically different is to use a limited number of *a priori*, planned comparisons, or t-tests. As long as the number of planned comparisons are less than $r - 1$, where r is the total number of levels in the experimental design, the probability of a type I error (incorrectly rejecting the null hypothesis) remains at the stated probability of falsely rejecting the null hypothesis, typically $p \leq 0.05$ (McGuigan, 1993).

Planned comparisons have three advantages. First, by *a priori* planning for a limited number of statistical comparisons, the researcher must be clear as to which effects are most important for study. This "budget" for statistical analysis disciplines the planning of the experiment and its design. Second, the post hoc, *a posteriori*, statistical tests which must follow the omnibus F-test are conservative in nature and smaller probabilities for rejecting the null hypothesis are required. This conservative approach may prevent acceptance of marginal experimental effects. This is not always a problem, but it should be considered. Third, the planned comparisons obviates the omnibus F-test and the post hoc statistical tests. With planned comparisons it is no longer necessary to perform the omnibus F-test, and therefore the post hoc tests.

A potential problem with planned comparisons is that this approach inherently limits serendipitous discoveries of unanticipated, statistically significant effects. If one does not anticipate an effect prior to the start of the experiment no provisions are made for performing inferential statistics. In the authors' view, such serendipitous discoveries are important to scientific advancement, but they also call for another, planned experiment for validation before publication. In a subsequent experiment limited pairwise comparisons again might be employed.

In general, the omnibus F-test, the post hoc tests, and the limited planned comparisons all have merit, and as long as the values and limits of each test are understood, each can be used effectively. In this experiment, the authors believed that the direction but not the magnitude of the results were expected from the literature. Largely for this reason, limited planned comparisons were chosen for statistical tests. It is important to stress, however, that the same major conclusions from the experiment would have been reached with any of the statistical approaches discussed above, because the effects were both robust and consistent with the literature.

ACKNOWLEDGMENTS

The authors would like to express their thanks to Dr. Peter Boyce and Professor Christopher Cuttle for their critique of the experiment, and to Dr. William Perez of the Federal Highway Administration for providing space and time to do the experiment, which also formed the basis for the senior author's Master's thesis.

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Figure 1. Relationship of target, target background and target surrounc

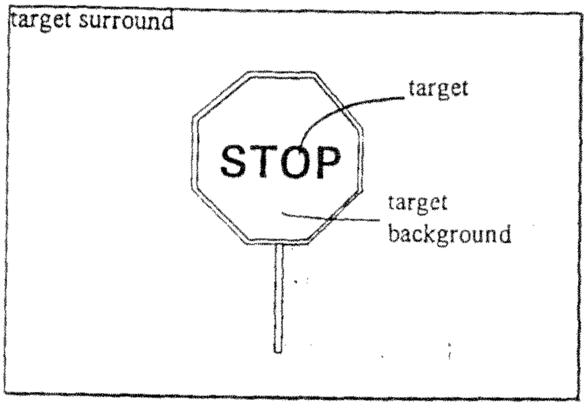

Figure 2. Magnocellular and parvocellular responses. Adapted from Kaplan and Shapely (1986).

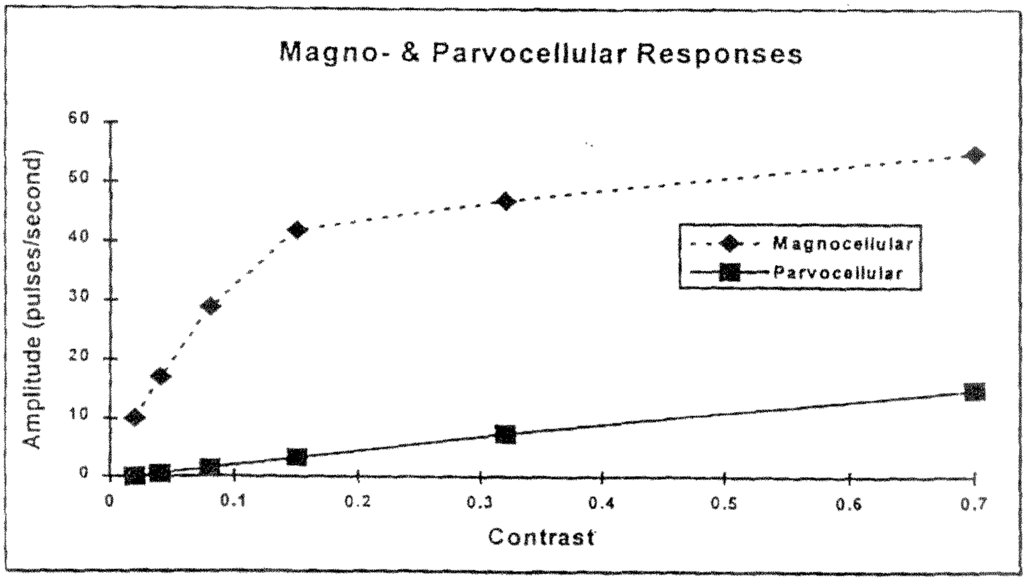

Figure 3. Design schematic of experimental setup.

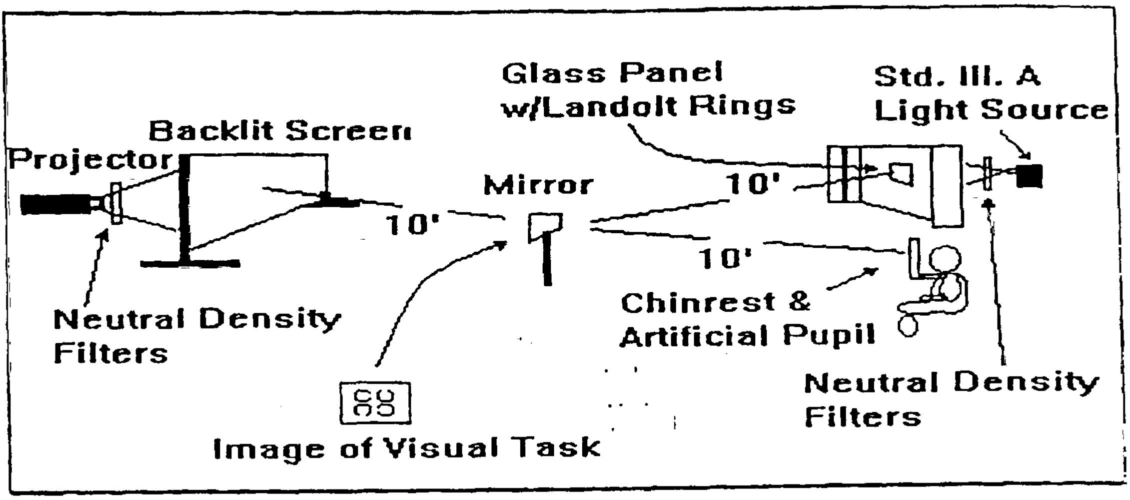

Figure 4a. Narrow border width.

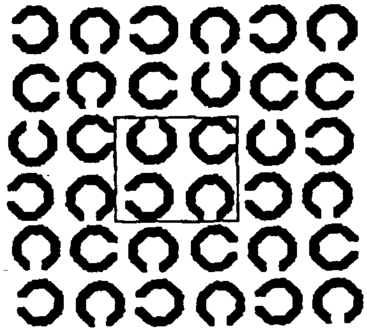

Figure 4b. Medium border width

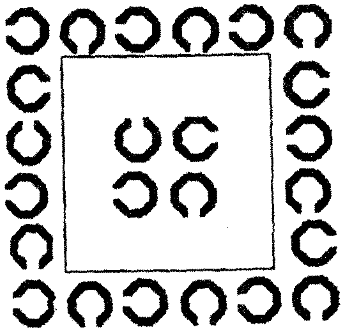

Figure 4c. Large border width.

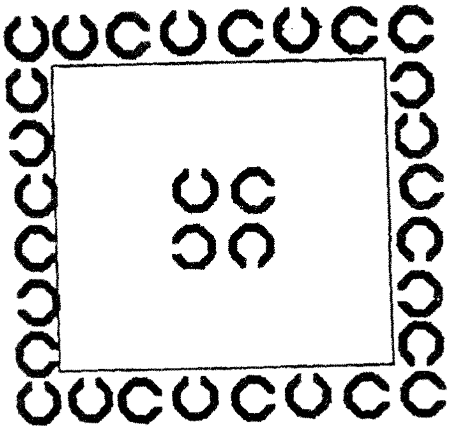

Figure 5. Response time versus contrast (data were collapsed across border width and field luminance).

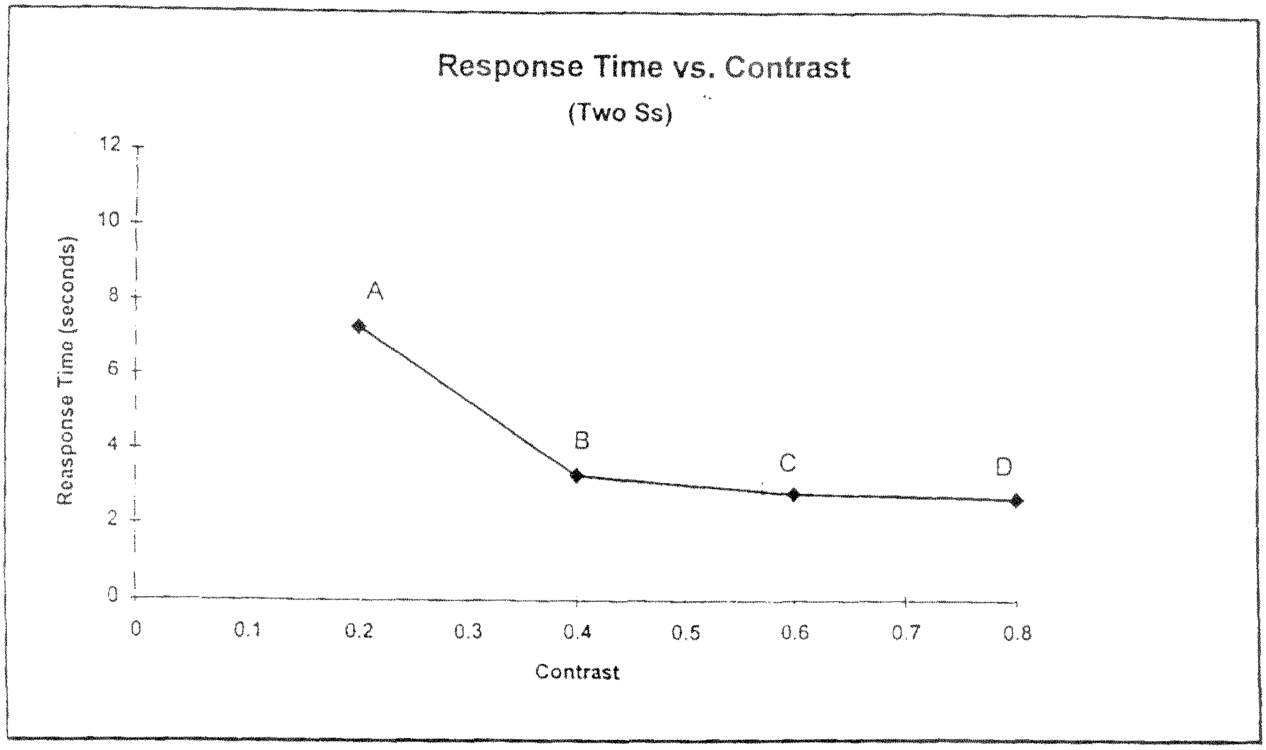

Figure 6. Response time versus border width (data were collapsed across contrast and field luminance).

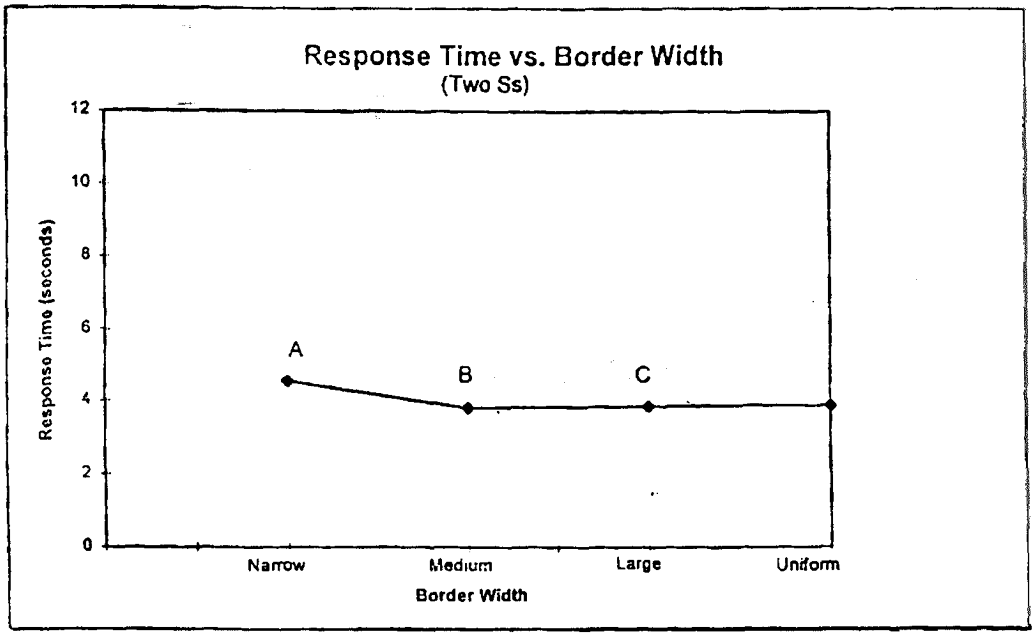

Figure 7. Border width and contrast interaction (data were collapsed across field luminance).

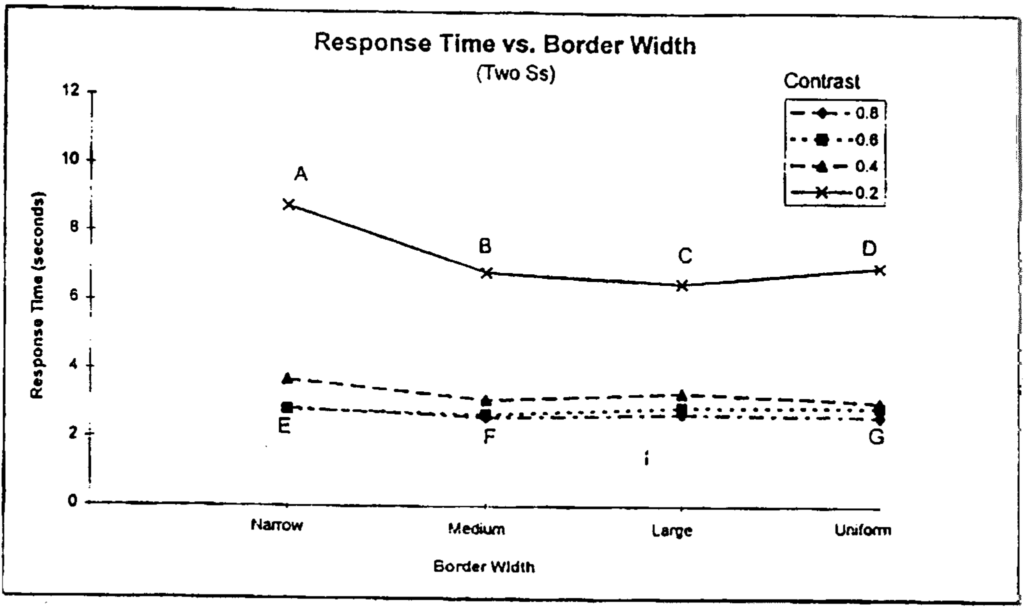

Figure 8. Border width and surround field luminance interaction (data were collapsed across contrast).

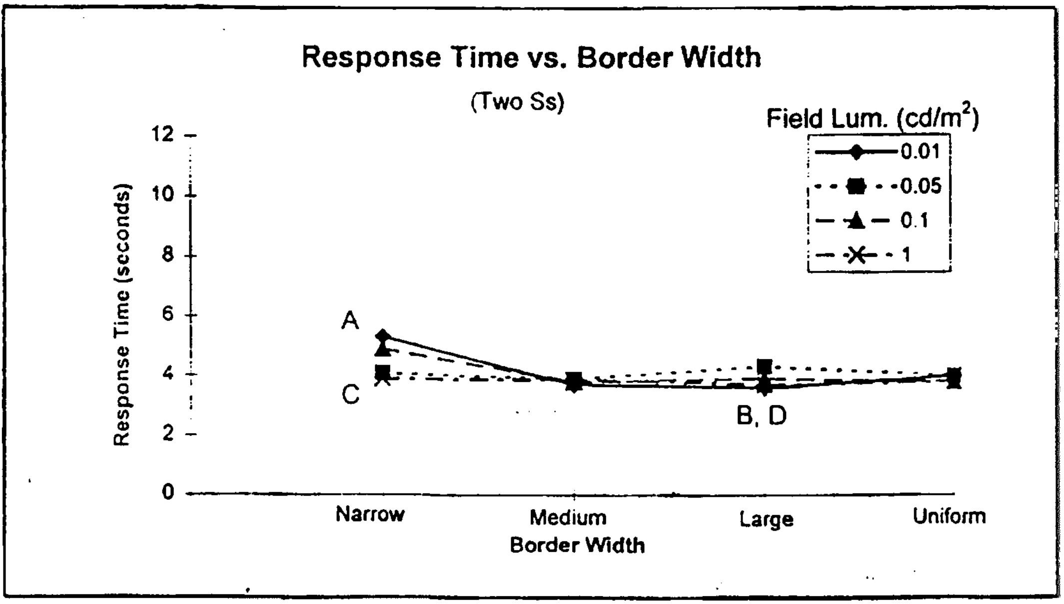

Figure 9. Surround field luminance and contrast interaction.

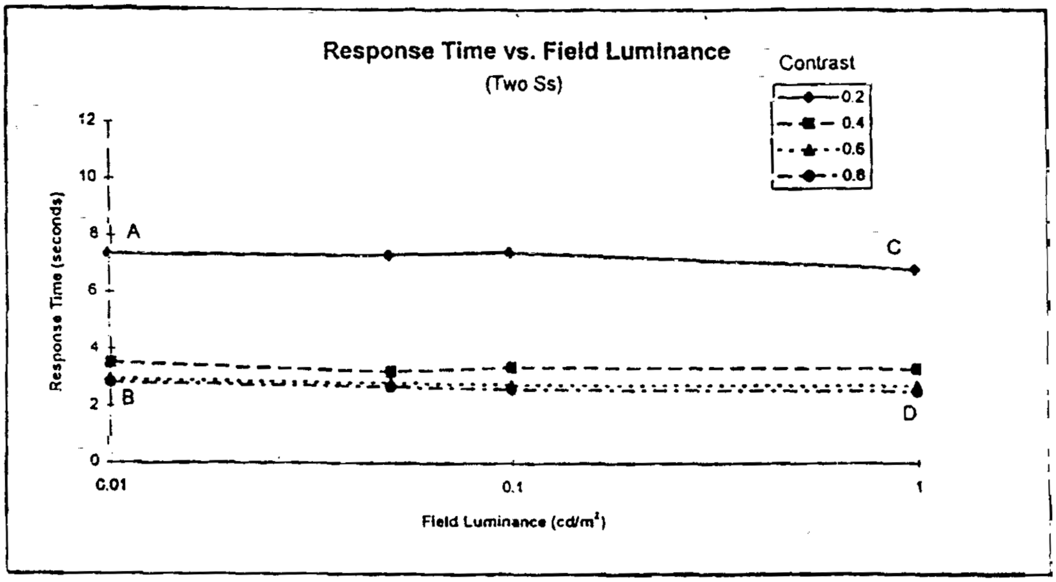

Figure 10. Subjective response versus contrast.

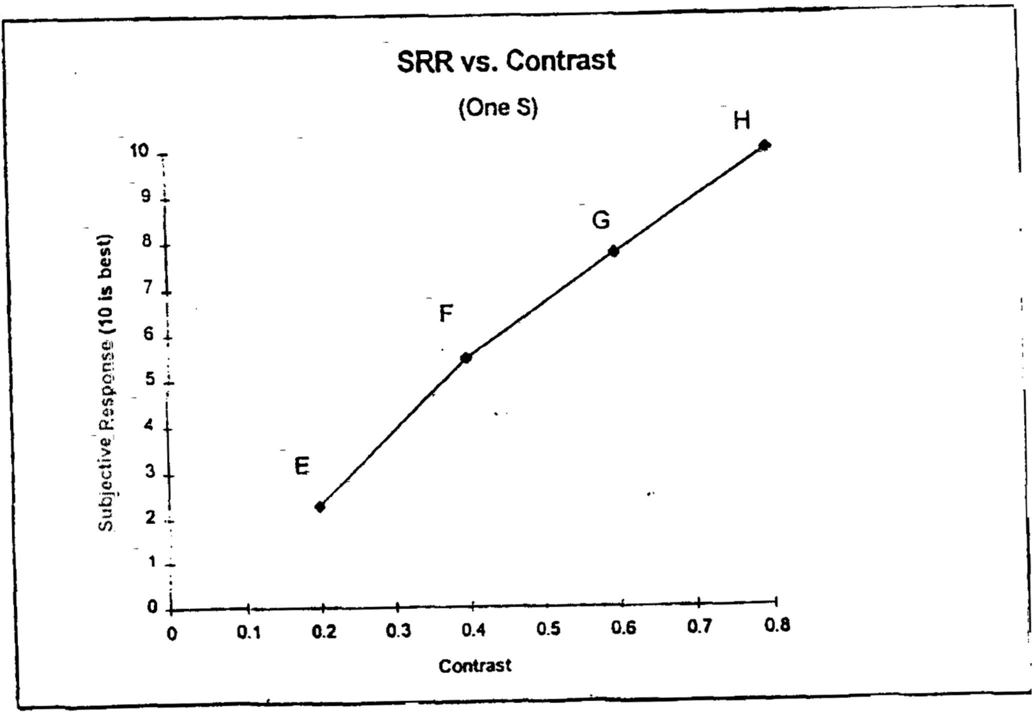

Figure 11. ΔT_{vis} and 1/4 the measured response time versus contrast.

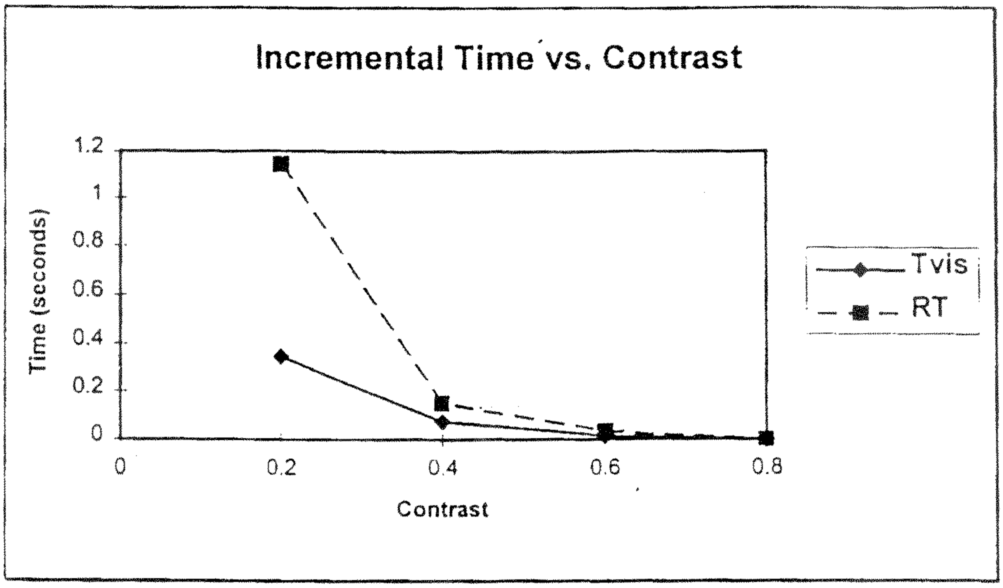

Table 1. Limited pairwise comparison summary for response times. (Significance for main effects = 1.645, for 2-way interactions = 1.658.)

Variable(s)	Levels	Results	Figure,points
Contrast	0.2 to 0.4	significant (t = 20)	5 , A to B
	0.4 to 0.6	significant (t = 6.4)	5 , B to C
	0.4 to 0.8	significant (t = 8.54)	5 , B to D
Border Width	Narrow to Medium	significant (t = 3.18)	6 , A to B
	Medium to Large	not significant (t = 0.26)	6 , B to C
	Narrow to Large	significant (t = 3.1)	6 , A to C
Border Width x Contrast	Nar. (0.2) to Med. (0.2)	significant (t = 3.43)	7 , A to B
	Unif. (0.2) to Unif. (0.8)	significant (t = 11.53)	7 , D to G
	Nar. (0.2) to Nar. (0.8)	significant (t = 12.94)	7 , A to E
	Nar. (0.8) to Med. (0.8)	significant (t = 2.15)	7 , E to F
	Med. (0.2) to Large (0.2)	not significant (t = 0.73)	7 , B to C
Border Width x Field Lum.	Nar. (0.01 cd/m^2) to Nar. (1 cd/m^2)	significant (t = 2.73)	8 , A to C
	Large (0.01 cd/m^2) to Large (1 cd/m^2)	not significant (t = 0.25)	8 , B to D
Field Lum. x Contrast	0.01 cd/m^2 (0.2) to 1 cd/m^2 (0.2)	not significant (t = 0.87)	9 , A to C
	0.01 cd/m^2 (0.8) to 1 cd/m^2 (0.8)	significant (t = 2.8)	9 , B to D

Table 2. Limited pairwise comparison summary for subjective ratings of readability. (Significance for main effects = 2.12.)

Variable(s)	Levels	Results	Figure, points
Contrast	0.2 to 0.4	significant (t = 27.8)	10 , E to F
	0.4 to 0.6	significant (t = 16.6)	10 , F to G
	0.6 to 0.8	significant (t = 24.8)	10, G to H
Border Width	Narrow to Medium	not significant (t = 0.27)	not illustrated
	Medium to Large	not significant (t = 0.03)	not illustrated
	Narrow to Large	not significant (t = 0.24)	not illustrated
Border Width x Contrast	Narrow (0.2) to Large (0.2)	not significant (t = 0.0)	not illustrated
Field Luminance	0.01 cd/m^2 to 0.05 cd/m^2	not significant (t = 0.12)	not illustrated
	0.05 cd/m^2 to 0.1 cd/m^2	not significant (t = 0.12)	not illustrated
	0.01 cd/m^2 to 1 cd/m^2	not significant (t = 0.25)	not illustrated
Field Luminance x Contrast	0.01 cd/m^2 (0.2) to 1 cd/m^2 (0.2)	not significant (t = 0.0)	not illustrated

Table 3. Relative visual performance model (Rea and Ouellette, 1991) comparison values with experiment.

	Experiment	RVP Model Values
Age	50	50
Size	4.9×10^{-7} Ω	2×10^{-6} Ω*
Contrast	0.2, 0.4, 0.6, 0.8	0.2, 0.4, 0.6, 0.8
Background Luminance	7 cd/m^2	7 cd/m^2

* The smallest size available in the RVP model