SUBJECTIVE PREFERENCES FOR THE RED COLOR OF STOP SIGNS: IMPLICATIONS FOR THE DESIGN OF HIGH-INTENSITY-DISCHARGE HEADLAMPS

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16. Abstract

The development of high-intensity-discharge (HID) headlamps has raised questions regarding the color rendition of objects they illuminate. The reason for this concern is that HID light sources, in comparison to tungsten-halogen light sources, emit proportionally less energy in the long-wavelength end of the visible spectrum--precisely in the most reflective wavelength region of retroreflective red stop signs. A likely consequence of the use of HID headlamps is a colorimetric shift of stop signs.

This study was designed to address empirically the consequences of colorimetric shifts of red sign materials in different colorimetric directions. Forty-eight subjects (of both sexes and three age groups) were shown individual small color samples under controlled lighting conditions. Their task was to indicate, on each trial, whether the sample color was acceptable for stop signs. At the end of each experimental session, subjects were asked to select a single most appropriate color for stop signs from among 16 simultaneously presented color samples.

There are two main findings. First, there is an overwhelming agreement among observers concerning the most appropriate red color for stop signs out of the 16 colors presented. Second, observers are differentially sensitive to colorimetric shifts in different directions from this most appropriate color. From among the investigated colorimetric-shift directions, subjects were most sensitive to hue shifts towards orange, while relatively insensitive to saturation shifts towards pink. Consequently, designers of HID headlamps should try to minimize the extent of colorimetric shifts of red sign materials towards yellow.

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CONTENTS

INTRODUCTION

The development of high-intensity-discharge (HID) headlamps has raised questions regarding the color rendition of objects they illuminate. The reason for this concern is that HID light sources, in comparison to tungsten-halogen light sources, emit proportionally less energy in the long wavelength end of the visible spectrum--precisely in the most reflective wavelength region of retroreflective red stop signs.

Our previous analytical study (Simmons, Sivak, and Flannagan, 1989) evaluated the colorimetric properties of retroreflective traffic signs when illuminated by HID headlamps. Two aspects were investigated: (1) colorimetric shift of individual sign materials when illuminated by HID light sources as opposed to tungsten-halogen, and (2) colorimetric separations of the red sign material from the yellow, orange, and brown sign materials when illuminated by HID light sources. Spectral reflectances of sign materials and spectral power distributions of HID (and tungsten-halogen) light sources were used to derive the CIE tristimulus values for the sign materials. These values were then transformed into the CIELAB space--a perceptually uniform color space. The results of the analyses indicate that the magnitude of the colorimetric shift increased with increasing correlated color temperature of the light source. The resulting colorimetric separations of red from yellow, orange, and brown for the HID light sources also tended to increase with increasing correlated color temperature.

The present study was designed to address empirically the consequences of colorimetric shifts of red sign materials in different colorimetric directions. Subjects were shown individual color samples under controlled lighting conditions. Their task was to indicate, on each trial, whether the sample color was acceptable for stop signs. At the end of each experimental session, subjects were asked to select a single most appropriate color for stop signs from among all simultaneously presented color samples.

An implicit assumption underlying this research is that subjective preference is related to performance: stimuli that are closer to the most preferred stimulus lead to better performance in terms of measures such as percent correct identification, reaction time, etc. Although direct evidence confirming this assumption does not exist, there is some indirect evidence. Stimulus-response situations that are compatible with the population stereotype lead to shorter reaction times than situations that are incompatible with the population stereotype (Kantowitz and Sorkin, 1983).

METHOD

Tasks

Subjects were asked to perform two tasks. The first task involved indicating whether a given color sample was acceptable for stop signs. The second task consisted of selecting one of 16 simultaneously presented color samples as the most appropriate one for stop signs.

Equipment

A schematic diagram of the experimental setup is shown in Figure 1. The subject was seated behind a table that had matte black paper on the top surface. The black paper served as the background on which the color samples were presented. On the top of the table was an enclosure that was painted flat black. The enclosure had two openings opposite each other. One opening allowed the subject to view the color samples, and the other opening allowed the experimenter to present the samples and record the responses. The top part of the enclosure contained a controlled light source (Macbeth® Examolite® D7500, designed to simulate CIE Standard Source D_{75}). The viewing distance was approximately 45 cm (depending on the height of the subject).

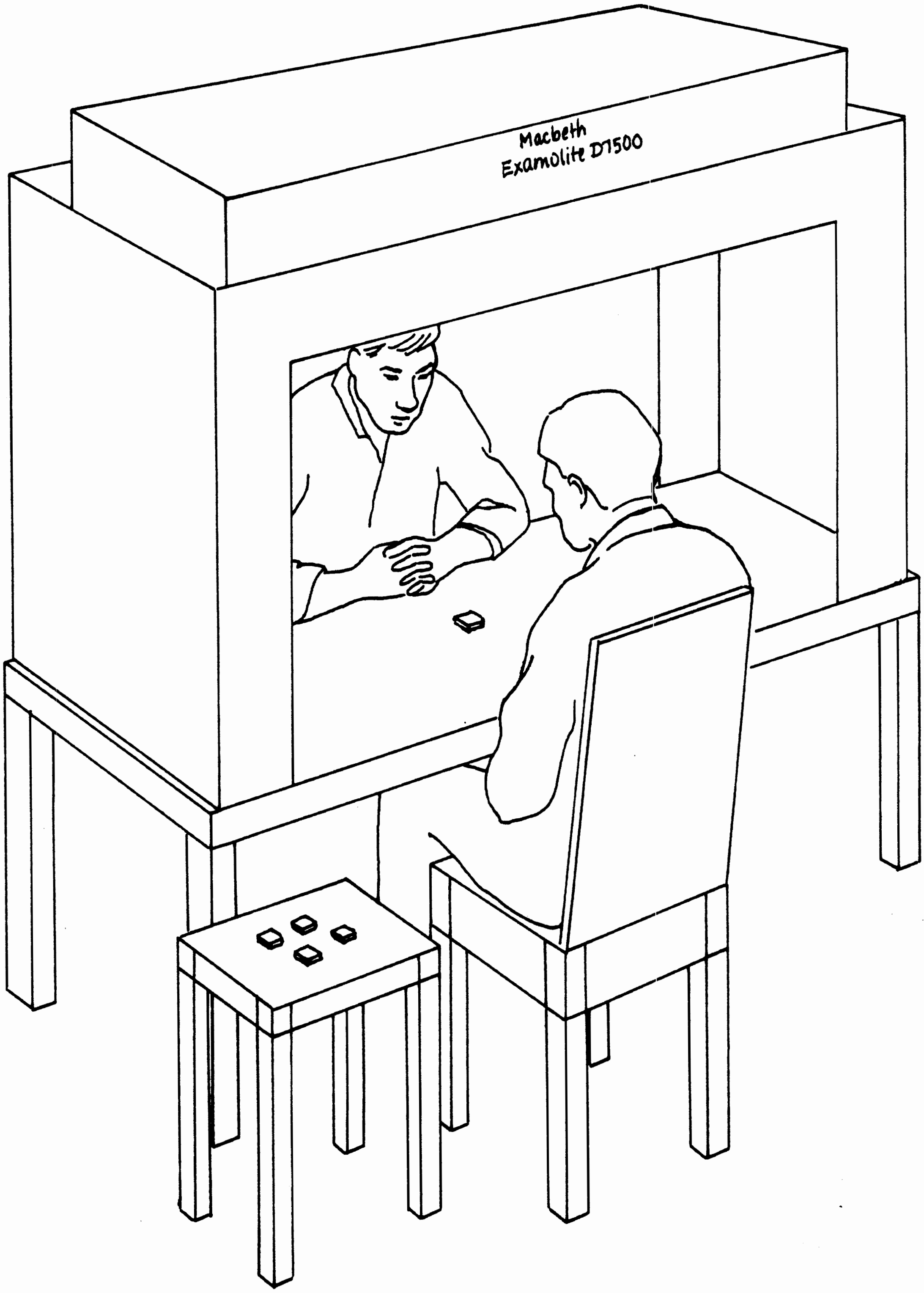

Figure 1. A schematic of the experimental setup.

Color samples

Sixteen glossy Munsell® Color Chips were selected as the color samples. They were all Munsell® value 4, and measured 1.7 cm (width) x 2.1 cm (height). The longer dimension of the color sample subtended approximately 2.7°, corresponding to the visual angle subtended by a standard (76 cm [30 in]) stop sign at 16.3 m. Figure 2 shows the general location of the color samples in the CIE (1931) color space, while Figure 3 indicates the specific locations of the individual color samples. The Munsell® notations and the corresponding CIE x,y chromaticity coordinates of the color samples (obtained by using the CIE Munsell® Conversion Software Program) are shown in Table 1.

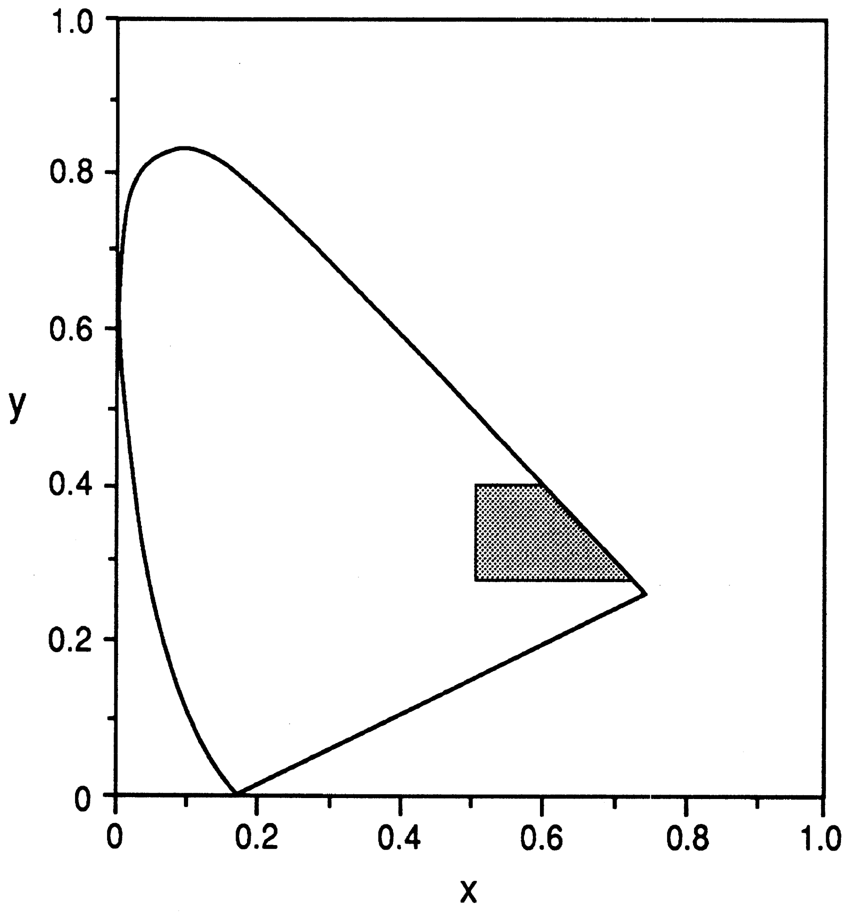

Figure 2. The general location of the color samples in the CIE (1931) color space.

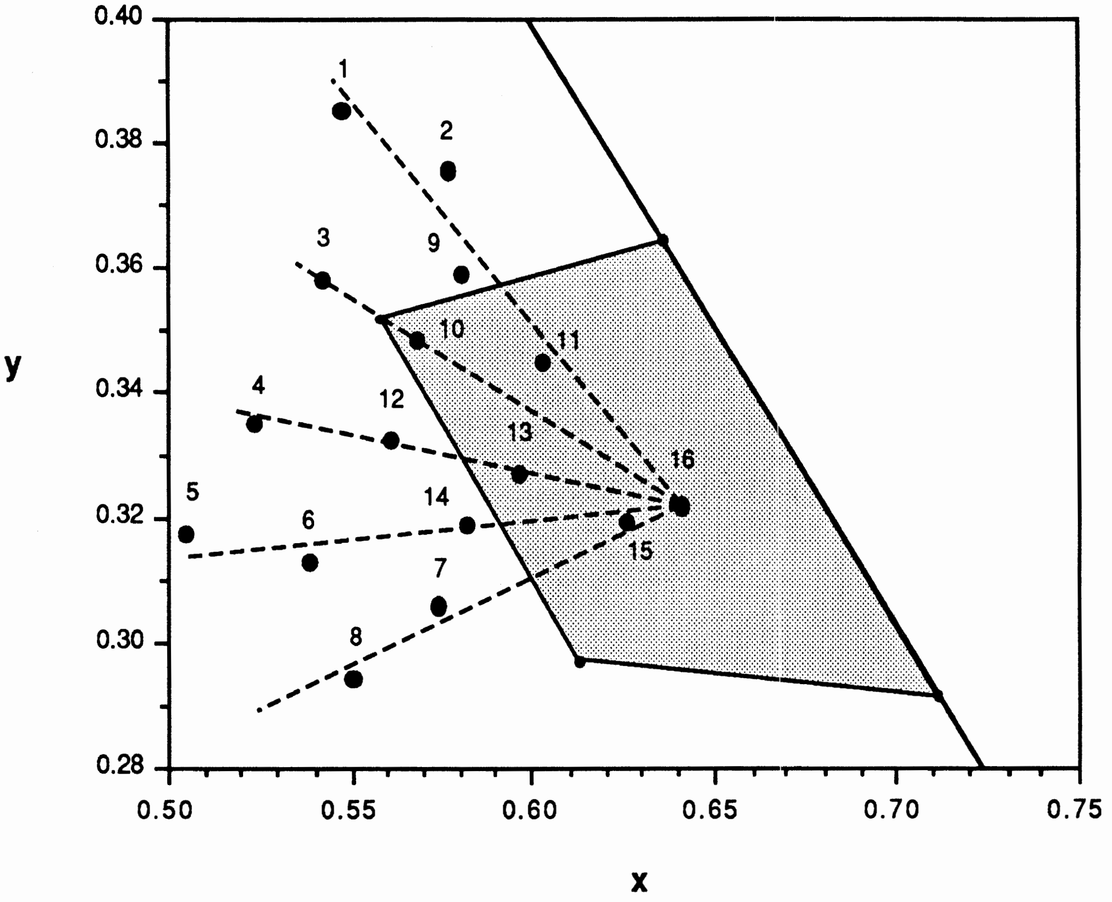

Figure 3. Color samples in relation to a section of the CIE (1931) color space. The shaded region corresponds to the current FHWA daytime specifications for the red Type III retroreflective sign materials. The dotted lines indicate that the color samples could be considered as being on one of five different directions of colorimetric shifts radiating from color sample 16.

Table 1.
Color samples used in the study.

Color Sample	Munsell® Notation	CIE (1931) Chromaticity Coordinates	
		x	y
1	2.5YR 4/10	.544	.386
2	1.25YR 4/12	.577	.376
3	10R 4/10	.539	.361
4	7.5R 4/10	.522	.338
5	5R 4/10	.500	.318
6	5R 4/12	.534	.313
7	5R 4/14	.568	.306
8	3.75R 4/14	.550	.294
9	10R 4/12	.576	.362
10	8.75R 4/12	.568	.348
11	8.75R 4/14	.603	.345
12	7.5R 4/12	.558	.335
13	7.5R 4/14	.593	.330
14	6.25R 4/14	.582	.319
15	7.5R 4/16	.623	.322
16	7.8R 4/17.2	.641	.322

As is evident from Figure 3, the color samples were selected to evaluate colorimetric shifts in five directions from the approximate center of the current FHWA daytime color-specification limits for Type III (encapsulated lens) sign materials (McGee and Mace, 1987). These shifts involve different degrees of changes in hue and saturation from sample 16. Shifts parallel with the adjacent locus line involve changes in hue. [Simmons, Sivak, and Flannagan (1989) found that the colorimetric shifts due to the change from tungsten-halogen to seven different HID light sources were generally in this direction.] On the other hand, shifts towards $x = .33$, $y = .33$ (shifts approximately parallel with the x axis) involve changes in saturation. The shifts in the directions of color samples 1 and 3 were generally perceived as changes towards orange, while shifts in the directions of samples 4, 5, and 8 were generally perceived as changes towards pink.

Subjects

There were 48 subjects in the study, with 16 subjects (8 males and 8 females) in each of the following age groups: younger, middle-aged, and older. The younger subjects ranged from 16 to 20 years (mean 18.4), the middle-aged subjects from 35 to 43 years (mean 38.1), and the older subjects from 60 to 69 years (mean 64.4). The subjects were selected from respondents to newspaper advertisements, and from our list of subject volunteers. Each subject was given a brief color-vision test using a Titmus® Vision Tester. The criterion for participation in the study was no more than one error out of the five color plates. Subjects were paid for their participation. None of the subjects had any affiliation with The University of Michigan Transportation Research Institute.

Design

The first task, dealing with color acceptability, consisted of 32 trials (16 color samples x 2 replications). A different order of the 32 stimuli was generated for each subject. The order was random, except for the following constraints: (1) each of the 16 color samples appeared first for one subject in each age group, and (2) each of the 16 color samples appeared once in the first half and once in the second half of the set of 32 trials.

The second task, dealing with color appropriateness, consisted of one trial only. Each subject was shown a different randomized arrangement of the 16 color samples divided into four rows of four samples each (covering approximately 30 cm x 30 cm).

Procedure

The testing was performed in a windowless room, with the Examolite® being the only source of illumination. Subjects were tested individually. The instructions for the first task were as follows:

> In this part of the study, you will be shown several small color samples. We would like you to tell us, for each sample, whether the color shown is acceptable for stop signs. If it is acceptable, then say "yes;" if it is not acceptable, say "no."

The instructions for the second task were as follows:

> In this last part of the study, you will be shown several small color samples at the same time. Please select the one that you believe is the most appropriate one for a stop sign.

The actual testing took about 15 minutes to complete.

RESULTS AND DISCUSSION

Selection of the most appropriate color (Task 2)

The selections of the single most "appropriate" color from among the 16 color samples are summarized in Table 2.

Table 2.
The selections of the single most appropriate color.

Color Sample	The Most Appropriate Color (%)
16	90
13	4
15	2
11	2
7	2
All other samples	0

The main finding from this task is that 90% of subjects agreed on sample 16 as the most appropriate color for stop signs. The remaining 5 subjects (10%) were distributed uniformly among the age and sex subgroups (2 males and 3 females; 2 younger, 2 middle-aged, and 1 older).

Acceptability of individual color samples (Task 1)

Effect of color sample. The percentages of "acceptable" responses by color sample are shown in Figure 3.

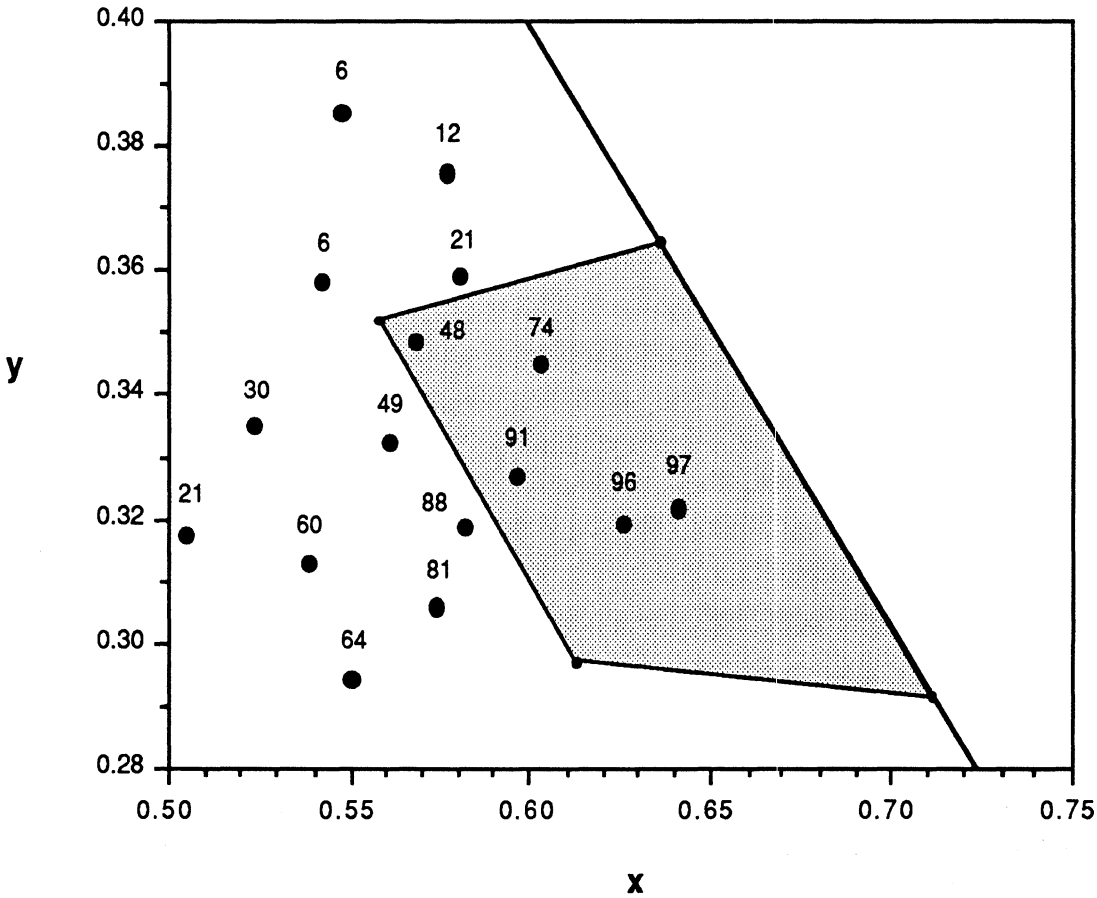

Figure 3. Percentages of "acceptable" responses by color sample.

A major finding, evident in Figure 3, is that colorimetric shifts in different directions from the most appropriate color (sample 16) lead to different decrements in the percentages of "acceptable" responses. Colorimetric shifts that involved primarily saturation changes towards pink had relatively minor effects on the percentages of "acceptable" responses. On the other hand, colorimetric shifts that involved primarily hue shifts towards orange resulted in substantial decrements of "acceptable" responses.

The differential sensitivity to different colorimetric shifts was evident even within the current FHWA limits for daytime color. Furthermore, there was a substantial decrement of "acceptable" responses within these limits. For example, for a color sample in the upper left corner of the limits (sample 10), only about a half of the responses were "acceptable."

Each of the 16 color samples was shown on the first trial for three subjects (one in each age group). The analysis of these first trials confirms, in general, the differential sensitivity to different colorimetric shifts. "Not acceptable" responses were obtained only for samples in the upper left section of the tested region (samples 1, 2, 3, 4, 9, and 10). Specifically, out of three responses, sample 3 was "not acceptable" three times, sample 9 two times, and samples 1, 2, 4, and 10 one time each.

Effect of sex of subjects. The percentages of "acceptable" responses by color sample and sex of subjects are shown in Table 3.

Table 3.
Percentages of "acceptable" responses by color sample and sex of subjects.

Color Sample	Sex		Mean
	Males	Females	
1	4	8	6
2	17	6	12
3	4	8	6
4	17	44	30
5	17	25	20
6	54	67	60
7	75	88	81
8	67	40	64
9	21	23	22
10	44	52	48
11	81	67	74
12	48	50	49
13	96	85	89
14	88	90	88
15	98	94	96
16	100	94	97
Mean	52	54	53

The data in Table 3 indicate that males and females had similar overall percentages of "acceptable" responses (52 and 54%). Furthermore, the general patterns of acceptability of individual color samples were also similar. (The product-moment correlation coefficient between the two sets of the 16 means was $r = .954, p < .001$.)

Effect of age of subjects. The percentages of "acceptable" responses by color sample and subject age group are shown in Table 4.

Table 4.
Percentages of "acceptable" responses by color sample and age group.

Color Sample	Age Group		
	Younger	Middle-Aged	Older
1	6	0	12
2	12	0	22
3	3	3	12
4	34	28	28
5	19	34	9
6	53	69	59
7	81	78	84
8	69	62	59
9	28	9	28
10	56	41	47
11	78	69	75
12	56	44	47
13	88	91	94
14	91	88	88
15	97	97	94
16	94	97	100
Mean	54	51	54

The data in Table 4 indicate that the three age groups had similar overall percentages of "acceptable" responses (54, 51, and 54%). Furthermore, the general patterns of acceptability of individual color samples were also similar. (The product-moment correlation coefficients for the three age pairs of the 16 means were $r = .952$, .963, and .977; in each case $p < .001$.)

Effect of replication. The percentages of "acceptable" responses by color sample and replication are shown in Table 5.

Table 5.
Percentages of "acceptable" responses by color sample and replication.

Color Sample	Replication	
	First	Second
1	10	2
2	15	8
3	10	2
4	38	23
5	27	15
6	71	50
7	81	81
8	62	65
9	25	19
10	52	44
11	77	71
12	54	44
13	92	90
14	94	83
15	100	92
16	98	96
Mean	57	49

The data in Table 5 indicate that there was a tendency for subjects to find samples more "acceptable" on the first replication than on the second replication (57 versus 49%). However, the general patterns of acceptability of individual color samples were similar. (The product-moment correlation coefficient between the two sets of the 16 means was r = .987, $p < .001$.)

Range effect. A range effect or context effect (e.g., Lulla and Bennett, 1981) occurs when responses to a particular stimulus are affected by stimuli presented prior to the stimulus in question. There is evidence that in the present study the *absolute* level of "acceptable" responses was affected by a range effect. Specifically, the overall percentage of "acceptable" responses on the first trial was 81% versus 57% for the first 16 trials and 49% for the second 16 trials. A possible explanation is that as subjects ascertained the range of stimuli being presented, they tightened their criteria of what constitutes an "acceptable" color. On the other hand, the *differential* sensitivity to shifts in different directions from the "most appropriate" color was present already in the first-trial data, and it remained throughout the experimental session.

Relation to color matching. The general pattern of the present results (see Figure 3) is consistent with the differential precision of color matching (MacAdam, 1942). In this part of the color space, the precision of color matching is least sensitive in the general directions for which we have obtained the smallest decrement in "acceptable" responses (i.e., primarily changes in saturation); conversely, the precision of color matching is most sensitive in the general directions for which we have obtained the largest decrement in "acceptable" responses (i.e., primarily changes in hue).

Relation to color naming. The present study compliments recent studies investigating color naming of sign materials as a function of the illuminant (e.g., Collins, 1988; Hussain, Arens, and Parsonson, 1989; Arens, Saremi, and Simmons, 1991). In those studies subjects were shown color samples and asked to generate corresponding descriptive names. In this study subjects were given a functional color description (i.e., a stop sign) and asked to indicate which of a variety of color samples corresponded to it.

CONCLUSIONS

There are two main findings of this study. First, there is an overwhelming agreement among observers concerning the most appropriate red color for stop signs out of the 16 colors presented. Second, observers are differentially sensitive to colorimetric shifts in different directions from this most appropriate color. From among the investigated colorimetric-shift directions, subjects were most sensitive to hue shifts towards orange, while relatively insensitive to saturation shifts towards pink. One consequence of this finding is that certain colors that are *outside* of the current FHWA daytime limits for retroreflective sign materials are considered by observers to be *more* acceptable than certain other colors that are *within* these limits. The generality of these two major findings is confirmed by the fact that they were consistent across age and sex subgroups of subjects.

While the differential sensitivity to different colorimetric shifts was present throughout the experimental session, the overall percentage of positive responses decreased over the duration of the session. This may have occurred because the subjects' criteria for acceptable colors became more stringent as they ascertained the total range of stimuli to be judged. This suggests that the proportion of positive responses to marginal stimuli depends on the range of stimuli presented. If subjects had been shown colors well beyond the red region, such as blues and greens, they may have been more inclined to accept marginal reds. Because of these considerations, interpretation of the absolute levels of acceptance obtained here should be made cautiously.

The major practical implication of this study is that HID designers should try to minimize the extent of colorimetric shifts of red sign materials towards orange. An additional practical implication is that the current FHWA limits for the daytime color of stop signs allow colors that might not be acceptable to some observers.

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