NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

SUBMARINE BASE, GROTON, CONN.

REPORT NO. 1044

THE EFFECT OF SET SIZE ON TIME TO RECALL COLOR CODED INFORMATION

by

Alan R. Jacobsen

Naval Medical Research and Development Command
Research Work Unit M0100.001-1022

Released by:

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Commanding Officer
Naval Submarine Medical Research Laboratory

27 March 1985

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SUMMARY PAGE

PROBLEM:

To determine if up to twenty colors presented on a CRT screen can be accurately identified and to ascertain the effect of set size on the time to recall color-coded information.

FINDINGS:

All observers were able to accurately identify all twenty colors in a single session. Time to recall increased significantly for set sizes of two through seven but showed no further significant increase for set sizes of eight through twenty.

APPLICATION:

In situations of relatively low ambient lighting, such as in sonar or control rooms, many more than five or six colors can be used to color code information on CRT displays if the colors and within display background luminance are carefully chosen.

ADMINSTRATIVE INFORMATION

This information was conducted as part of the Naval Medical Research and Development Command Work Unit M0100.001-1022 - "Enhanced performance with visual sonar displays." It was submitted for review on 12 Mar 1985, approved for publication on 27 Mar 1985, and designated as NSMRL Report No. 1044.

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ABSTRACT

The ability of observers to accurately identify up to twenty different colors presented on a CRT screen was studied. The effect of set size on time to recall color-coded information was also investigated via a paired-associates paradigm in which each color was paired with a letter of the alphabet. On test trials the time between color presentation and the subject's verbal response with the appropriate letter were recorded.

All twenty subjects were able to identify accurately all twenty colors. For sets of two through seven colors, increases in set size resulted in significant rises in time to recall. Subsequent increases in set sizes, up to twenty, resulted in little or no further increase in time to recall. The time to recall was also found to vary significantly to the different colors. Although no statistical differences were found among 16 of the 20 colors, the other 4 yielded significantly slower times to recall.

Performance on this task did not correlate well with color differences that were measured by ΔE^*. This may have resulted from the colors being presented on a luminous background rather than a completely dark screen. ΔE^* was a poor indicator of time to recall as well as error rate during learning. Error rate and time to recall were found to be highly correlated.

INTRODUCTION

It is currently proposed to make use of colors in CRT displays on submarines instead of using only green phosphors. It has been suggested by researchers that this will enhance many aspects of performance (1-5). In general, the enhancement brought about by the use of color is dependent upon the type of task being studied. One of the most promising areas for color enhancement appears to be in the coding of information in both search and identification tasks. It is in these areas that color coding appears to have an advantage over many other coding schemes such as brightness and shape (5).

One of the most important factors concerning color coding is the number of colors that can be used in any given task. It has been found that under carefully controlled laboratory conditions, as many as one million colors can be discriminated (6). This however, is quite different from the number of colors that can be absolutely identified correctly in real world situations that are substantially less than ideal. Several studies have dealt with this problem and it is generally assumed that the maximum number of colors that can be accurately identified varies from three to ten depending on the conditions and the task involved (5). The lower estimates come from research done under very adverse conditions such as high ambient light levels in an aircraft cockpit (7). Under less adverse conditions it has been shown that as many as 24 colors can be correctly identified (8). This estimate, however, was obtained using colored papers and not CRT displays and under fairly ideal laboratory conditions. The range of suggested colors is hence quite large and optimum color sets are probably very much dependent on conditions and task.

A second question regarding the use of color as a coding scheme is how well they can be remembered and subsequently recalled. Sternberg (9) performed several studies that suggest that as set size increases, the time to recognize individual set elements increases linearly. However, this seems true only for sets that are not well learned. Clifton (10) demonstrated that there is no increase in time to recognition for set sizes from two to four if the sets are well learned. Recently, Jacobsen and Neri (11) have shown that there is no increase in time to recognition for color set sizes from two to seven again, if the list is well learned. These studies only dealt with whether or not an individual color belonged to the set in memory, that is, color recognition, and no attempt was made to identify the individual colors as in the Feallock, et.al. study. In that study no attempt was made to measure reaction time, however. Identification and recognition refer to slightly different tasks. As an example, one might recognize another person's face but not be able to identify where the person was previously seen. Hence, identification would appear to require a higher level of memory processing than mere recognition. In situations where up to 10 or more colors will be used, it is unknown how time to recall, which implies identification, will be affected by set size.

Another issue regarding the use of colors in CRT displays is how to generate sets that will result in optimal performance. It is generally agreed upon that this is achieved by maximizing color differences. The question then becomes how one measures and determines color differences. Carter and Carter (12, 13) have proposed the use of ΔE^* values as a method of measuring differences between colors presented on CRT screens. ΔE^* is an estimate of color difference based upon both the chromatic or hue difference between two colors and the brightness or intensity difference. It was originally designed to ascertain if two dyes were noticeably different from one another. Supposedly, the smaller the ΔE^* value, the more identical two colors appear. However, it is unclear whether ΔE^* values will be of use in determining large color differences, as between two different hues like yellow and red. Making such large difference comparisons may violate the original assumptions underlying the determination of ΔE^*. Carter and Carter report on several studies that seem to support the contention of using ΔE^* for large color differences, but no clear-cut answer has been determined. By comparing ΔE^* values and reaction times as well as error rates, it may be possible to assess how performance relates to large color differences as measured by ΔE^* values.

The present research is aimed at answering the following questions. First, whether as many as twenty colors, presented on a CRT screen under normal submarine conditions where the ambient light is fairly low, can be accurately identified. Second, how set size affects time to recall color-coded information. It is assumed that as the number of color-coded items increases, the time to recall the meaning of each item will increase, but it is not known what the relationship is. Third, whether time to recall color-coded information relates well with ΔE^* values. If so, this measure may be very helpful in generating new color sets in CRT displays, as Carter and Carter have pointed out. A paired-associates paradigm, where color stimuli are paired with letters of the alphabet, was used to study these questions. The color-letter pair sets were varied in number from two to twenty.

METHOD

Subjects.

Twenty color normal males, as verified by the A.O. Pseudo-Isochromatic plates, who were enrolled in the Naval Submarine School served as voluntary subjects. Their mean age was 20.1 years with a range of 18 to 31 years. Those who normally wore corrective lenses did so during the experiment.

Apparatus.

The subject was seated in front of an Advanced Electronics

Design Color Graphics and Imaging Terminal Model 512 at a viewing distance of 50 cm. The amount of ambient light falling on the screen was 0.45 fc. The stimuli consisted of twenty differently colored circles 1.5 cm (1.75 degrees of visual angle) in diameter presented in a four column by five row matrix on an achromatic background that had a luminance of 2.55 fL. A distance of 2.2 cm (2.5 degrees of visual angle) separated the circles horizontally and 1.1 cm (1.25 degrees of visual angle) vertically. The color stimuli were chosen so as to be easily discriminable by color normals. The CIE coordinates of the twenty colors and background are given in Table I. All photometric measures were made with a Spectra Pritchard model 1980A photometer. To arrive at CIE coordinates visual matches were made between the CRT stimuli and Munsell papers presented under Illuminant C. By measuring the Munsell papers, correction factors were computed and applied to the colorimetric measures of the unknown CRT stimuli. No attempt was made to equate the brightnesses of the colors; rather brightness differences were used to enhance discriminability.

A Digital PDP 11/04 computer was used to control the presentation of the stimuli on the AED terminal and to measure and record subject data. This computer was also connected to a Scientific Prototype Audio Threshold Detection Relay Model 761-G and an Electro-Voice Microphone Model 423A which were used to measure the subjects' verbal response times.

Procedure

The task consisted of a study-test paired associate paradigm. In the study phase, letters of the alphabet were paired with the colored circles by superimposing the appropriate letters on the circles. Subjects were allowed to observe the entire study display for as long as they wished.

During the test phase, one colored circle at a time was randomly chosen by the computer and presented in the middle of the CRT screen. The subject's task was to respond verbally with the appropriate letter. Time to recall (time from stimulus presentation to subject's response) and the actual response were both recorded. Time to recall was measured by an internal clock in the computer. The clock was started when the test circle appeared on the CRT screen and the subject's verbal response triggered the audio detection relay which stopped the clock. Subsequent to this the experimenter entered the subject's response into the computer via a keyboard. Once the entire learning set was presented, the study phase was reinitiated using the same set of color-letter pairs. The subject again controlled the length of time of this phase. A second test phase was then begun with a different random order of color stimuli presentations. This procedure of study-test was continued until the learning criterion of all responses correct in three consecutive test phases was met. The subject was then given an optional rest period after which a new learning set was then introduced and the

Table I. CIE (1931) coordinates for twenty colors and display background

Color	Y	x	y
Light Blue	14.84	.18	.16
Yellow	44.53	.42	.46
Red	3.14	.51	.29
Lime Green	56.1	.26	.54
Violet	1.21	.27	.15
Orange	18.45	.55	.37
Dark Green	1.33	.29	.54
Magenta	19.91	.20	.09
Medium Blue	1.38	.15	.08
Olive Green	1.63	.38	.49
Brown	1.00	.37	.42
Buff	30.17	.37	.28
Cyan	22.31	.22	.33
Maroon	0.88	.50	.32
Tan	8.08	.39	.37
Hot Pink	15.92	.42	.19
Dark Aqua	3.11	.20	.27
Slate	1.93	.23	.21
White	84.50	.23	.25
Dark Blue	0.25	.18	.12
Gray Background	5.89	.27	.28

entire procedure was repeated.

Each learning set consisted of two to twenty color-letter pairs. The order of presentation of set size was the same for all subjects as the set of two was always presented first followed by the set of three, four, etc. up to twenty. Each subsequent learning set consisted of the previous color-letter pairs plus one additional pair. For example, if the learning set of two consisted of blue-A and red-B, the set of three consisted of blue-A, red-B, and yellow-C. Although the order of set size presentation was the same for all subjects, the color order presentation was different for each subject. Consequently, only in the set size of 20 were the color sets identical for all subjects. Since the presentation of the letters followed the same alphabetical order (A,B,C,D,etc.) for all subjects, this counterbalancing ensured that the effect of set size was not confounded with whether some colors were more or less discriminable than others colors. The entire procedure took approximately one and a half to two hours and most subjects took at least one rest period during this time.

RESULTS

Color identification

Since all subjects met the learning criteria, it is obvious that they were able to accurately identify all twenty different colors presented on the CRT screen. This was achieved without the extensive amount of practice done in the Feallock, et al. (8) study as all subjects achieved criterion in one experimental session which lasted approximately two hours.

Reaction time and set size

The effect of set size on reaction time was analyzed by obtaining an average reaction time for each set size for each subject. This was achieved by computing the mean reaction time for responses that occurred in the last test phase presented for each set size. These data were then averaged across subjects and are presented in Figure 1. A test of linearity (14) was used to determine that the relationship between set size and time to recall was significantly different from linear ($F(17,361)=63.16$, $p<.01$). However, for set sizes two through seven, the relationship was not significantly different from linear. The same was also true for set sizes 8 through 14 and set sizes 15 through 20. In the latter two cases, it was also determined that the lines did not differ significantly from a slope of 0. In sets two through seven, the slope of the line was significantly different from 0 ($F(1,114) = 128.9$, $p<.01$).

A one-way repeated measures ANOVA revealed a significant effect of set size on reaction time ($F(18,342) = 33.76$, $p<.01$). Newman-Keuls means tests showed that the set sizes of two, three, four,

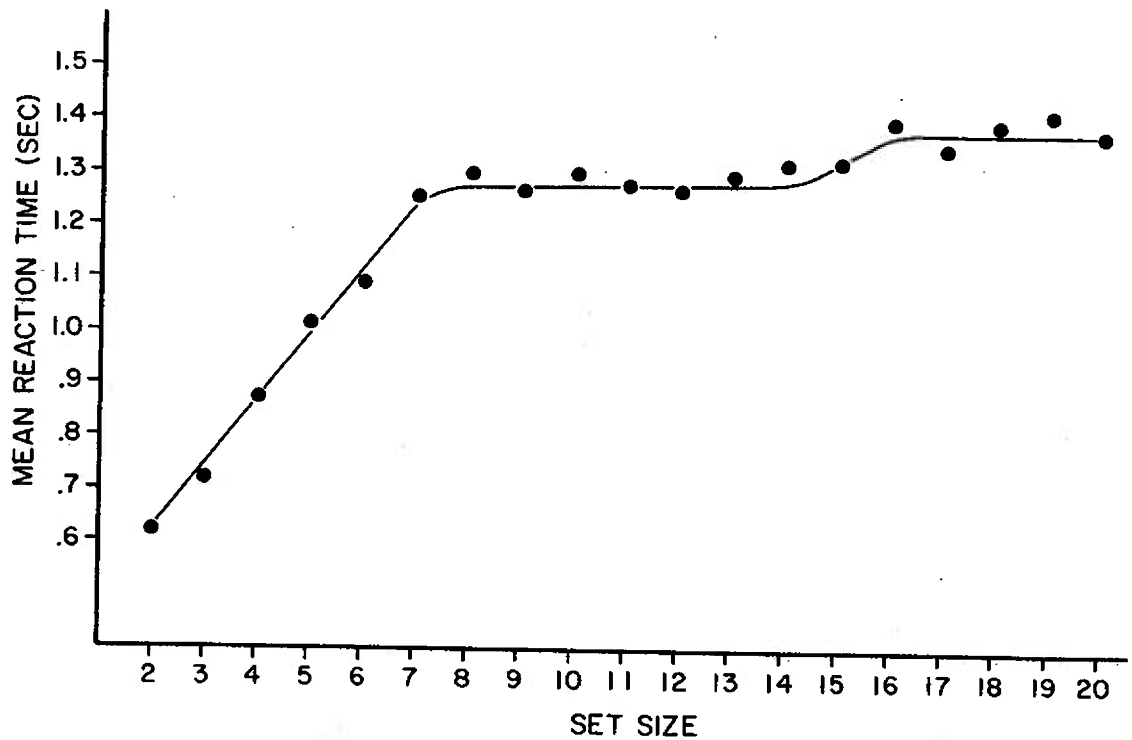

Figure 1. Mean reaction time plotted as a function of set size.

five and six all yielded significantly faster times to recall than those of all other set sizes. In addition, the set of two yielded significantly faster times than three, four, five and six ($p < .05$). The set of three yielded significantly faster times than four, five and six ($p < .01$). The set of four yielded significantly faster times than the sets of five and six and finally the set of five yielded a significantly faster time than the set of six ($p < .01$).

Reaction time as a function of color

The reaction times recorded during the last test phase presented in the set size of twenty were used to analyze the effect of color on reaction time. All colors were supposedly well-learned by this time and in addition, only in the set size of twenty was the color set identical for all subjects. The mean time to recall for each color can be seen in Figure 2. A one-way repeated measures ANOVA revealed a significant effect of color on time to recall ($F(19,361) = 7.67$, $p < .01$). Newman-Keuls means tests showed the following significant differences among the colors: olive, magenta, cyan, and dark aqua yielded slower times than white. Magenta, cyan, and dark aqua yielded slower times than dark blue, orange, red, slate, yellow, medium blue, tan, buff, and pale green. Finally both cyan and dark aqua yielded slower times than all of the other colors.

Color mistakes as a function of set size

Although all subjects reached the learning criterion of perfect responding during three consecutive test phases for all set sizes, numerous errors were made prior to reaching criterion. The mean number of errors made by all subjects for each set size is shown in Figure 3. A one-way repeated measures ANOVA determined that there was a significant effect of set size on the number of errors made prior to the subjects reaching the learning criterion. Newman-Keuls means tests revealed that the only significant difference was that the set of two yielded fewer errors than the set of 20. The correlation between number of errors and time to recall as a function of set size was 0.63 ($p < .01$).

Color mistakes as a function of color

The mean number of errors made for each color is shown in Figure 2. A one-way repeated measures ANOVA revealed a significant difference among the errors made for the various colors. Newman-Keuls means tests, however, revealed no significant pair-wise differences among the twenty colors at the .05 level. The correlation between time to recall and error rate as a function of color was 0.847 ($p < .01$).

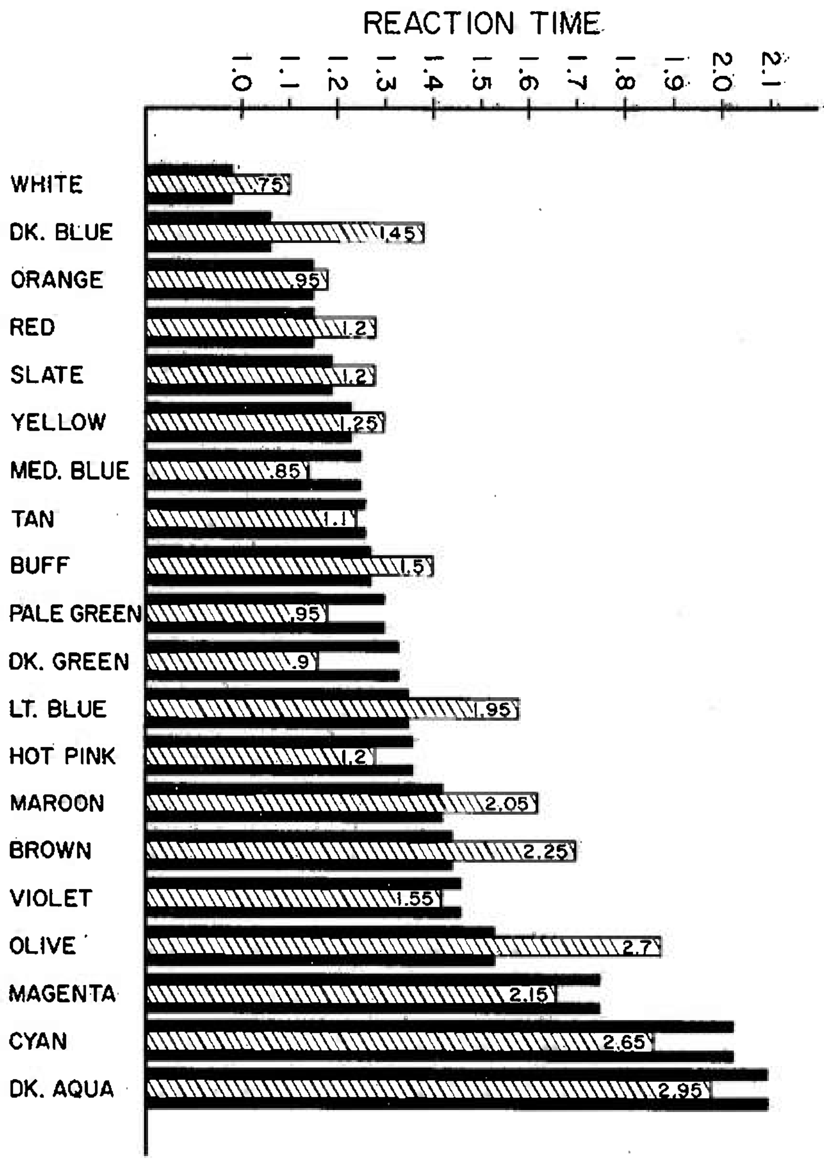

Figure 2. Mean reaction time (black outside bars) and mean errors during learning (white inside bars) as a function of color.

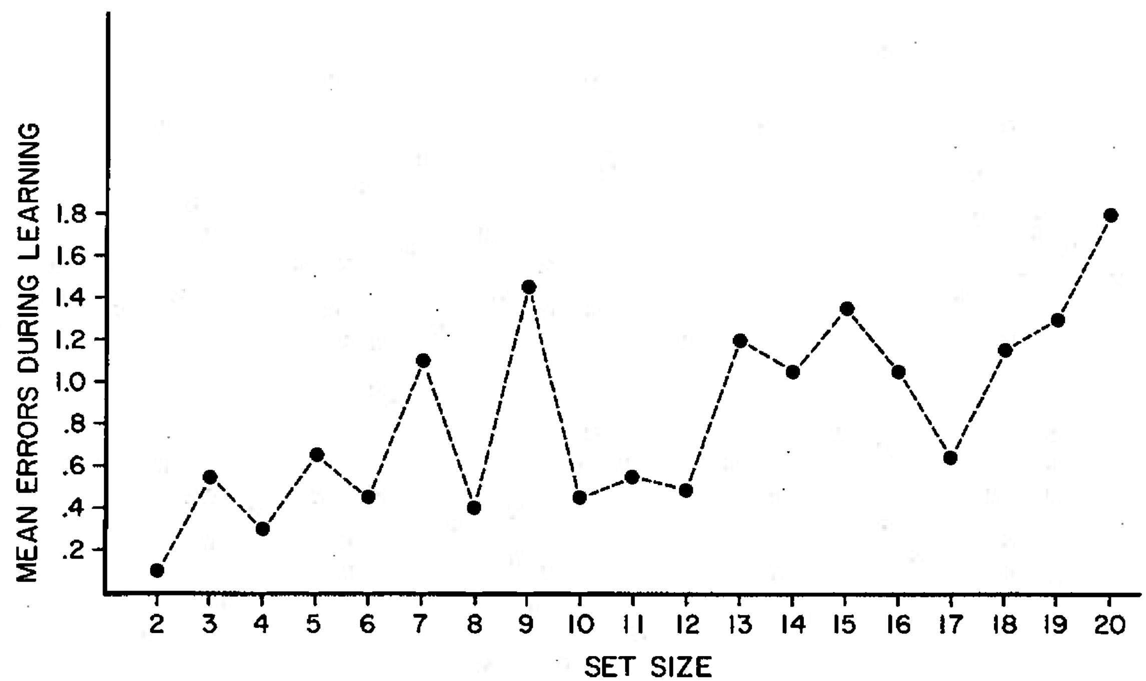

Figure 3. Mean errors during learning as a function of set size.

Time to recall, errors and ΔE^* values

ΔE^* values were calculated for all possible color pairs and these were analyzed in several ways. First an average ΔE^* value was calculated for each color. The correlation between these values and time to recall was -0.015 and the correlation between the former and number of errors was -0.21. The correlation between time to recall and the smallest ΔE^* values by color was found to be -0.035. The correlation between time to recall and the average of the two smallest ΔE^* values was -0.01. The correlation between the number of errors and the smallest ΔE^* value for each color was -0.255. The correlation between number of errors and the average of the two smallest ΔE^* values was -0.231. None of these correlations was statistically significant.

In addition, Table II gives the color pairs with the highest number of errors, along with their respective ΔE^* values. All color pairs with ΔE^* values of 31 or less are also shown in this table along with their respective number of errors. From this Table it can also be seen that ΔE^* values do not necessarily correlate well with apparent color confusions. For example, of the ten most confusable colors, as measured by number of errors made, while five had ΔE^* values less than 32, five had values greater than 47. Of the two color pairs confused the most, both had ΔE^* values less than 40. On the other hand, of the two color pairs with the lowest ΔE^* values, each was confused only once. Finally, it can be seen from Table II that of the 29 color pairs with ΔE^* values of 31 or less, 12 were never confused, six were confused only once and five were confused from two to four times.

DISCUSSION

As all subjects reached the learning criterion without any difficulty, it is certainly possible to accurately identify up to at least twenty colors on CRT displays under some conditions. The ambient lighting was fairly dim in this study (approximately 0.45 fc) and the background on the CRT display was set at about 2.55 fL. These are relatively optimal conditions for viewing CRT displays but certainly not exclusive to the laboratory setting.

The effect of set size on time to recall was somewhat unexpected. As set size increased for sets two through seven, there was a corresponding rise in time to recall. After that, further increases in set size resulted in little or no further increase in time to recall. In a study of the effect of set size on time to recognize colors (11) a slightly different effect was found. As set size increased from one to two, time to recognition increased but further increases in set size, up to seven, resulted in little or no further increases in time to recognition. In the present study, it would appear that once the limits of short-term memory are reached, which has been put by Miller (15) at seven items, plus or minus two, further increases in set size do not effect time to recall appreciably. Consequently, once a set of colors

Table II. Color confidence and ΔE^* values. First 10 pairs were all those confused 8 or more times. Remaining pairs are all those with ΔE^* values of 30 or less, arranged in order of number of confusions.

Color Pair	# Confusions	ΔE^*
Brown : Maroon	27	16
Olive : Dark Aqua	26	31
Dark Aqua : Slate	13	15
Yellow : Buff	11	88
Light Blue : Cyan	11	87
Cyan : Dark Aqua	10	47
Brown : Dark Blue	9	11
Olive : Tan	9	26
Magenta : Hot Pink	9	152
Violet : Magenta	8	153
Dark Green : Dark Aqua	4	28
Violet : Dark Blue	4	25
Brown : Tan	3	30
Violet : Medium Blue	3	25
Dark Aqua : Dark Blue	2	29
Maroon : Tan	1	29
Olive : Maroon	1	21
Dark Green : Dark Blue	1	20
Violet : Slate	1	12
Dark Green : Olive Green	1	9
Olive Green : Brown	1	8
Maroon : Slate	0	30
Violet : Brown	0	29
Dark Green : Maroon	0	28
Brown : Dark Aqua	0	28
Brown : Slate	0	27
Violet : Dark Aqua	0	26
Slate : Dark Blue	0	25
Violet : Maroon	0	25
Medium Blue : Slate	0	23
Olive Green : Dark Blue	0	19
Maroon : Dark Blue	0	18
Dark Blue : Brown	0	13

is well-learned and hence in long-term memory, set size will apparently have little or no effect on time to recall. Set size also does not appear to have much of an effect on the number of errors during learning.

Color had a substantial impact on time to recall. For sixteen of the twenty colors, although there was a steady rise in time to recall, as can be seen from Figure 2, there was no definitive break. However, four of the colors were substantially worse than the other sixteen. These were olive, magenta, cyan, and dark aqua. The last two resulted in quite appreciably slower times to recall. It should also be noted that the easiest color to identify was white. Although a one-way ANOVA found a significant effect of color on number of errors, Newman-Keuls tests found no significant pairwise differences. From Figure 2 it is apparent that some colors, such as dark aqua, cyan, and olive, were involved in many more mismatches than colors like white, orange, and medium blue. One should note that colors having higher reaction times also had higher error rates. In fact the correlation between error rate and time to recall by colors was highly significant. It appears that as colors become more difficult to discriminate, which results in higher error rates, the time to identify those colors also increases. Consequently, in choosing colors for CRT displays it becomes essential to make the colors as different as possible. The problem is to determine how to measure color differences. Carter and Carter (12) suggest using ΔE^* values as a measure of color differences. The notion of using ΔE^* values has only been minimally tested and it should be noted again that this measure of color difference was never intended to be used with very large color differences. It is unclear whether ΔE^* values correlate well with perceived color differences that are fairly large. Carter and Carter (12) report on a few studies that seem to suggest that it does. However, as they point out there are several shortcomings of ΔE^* one of which is that it does not take background luminance into account so that where the background is not completely black its use may be questionable. This was definitely supported in the present study in which the background luminance of the display was fairly high. No correlation between ΔE^* values and either number of errors or time to recall was found. Both of the latter measures are assumed to be dependent on the identifiability of colors and hence on color differences. Consequently, although using ΔE^* values might appear to be an easy solution for generating various color sets it should not be used when a display background is anything other than completley dark.

The overall results of this study suggest that a higher number of colors may be used for color coding than is generally recommended by the literature, at least for displays not subject to higher ambient light levels. In fact, if color sets were to be chosen more carefully than in the present study, it might be possible to generate a set of over 20 colors that would be easy to identify on an absolute basis. One problem, however, that the current study did not address is the question of simultaneous color contrasts which will affect color identification. For example, it is well known that a color presented in an area of high luminance will appear different than when it is presented in an area of low luminance. This problem is very much dependent upon the type of display in which the colors are to be incorporated. It is also an area in need of further investigation.

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The ability of observers to accurately identify up to twenty different colors presented on a CRT screen was studied. The effect of set size on time to recall color-coded information was also investigated via a paired-associates paradigm in which each color was paired with a letter of the alphabet. On test trials the time between color presentation and the subject's verbal response with the appropriate letter were recorded.

All twenty subjects were able to identify accurately all twenty colors. For

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Performance on this task did not correlate well with color differences that were measured by ΔE^*. This may have resulted from the colors being presented on a luminous background rather than a completely dark screen. ΔE^* was a poor indicator of time to recall as well as error rate during learning. Error rate and time to recall were found to be highly correlated.