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The Effect of a Redundant Color Code on an Overlearned Identification Task

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TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

ACRONYMS AND ABBREVIATIONS

GLM	General Linear Models
LF	large familiar
MANOVA	Multivariate Analysis of Variance
RT	reaction time
S-R	stimulus-response
SF	small familiar
SU	small unfamiliar

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SUMMARY

The possibility of finding redundancy gains with overlearned tasks was examined using a paradigm varying familiarity with the stimulus set. Redundant coding in a multidimensional stimulus has been demonstrated to result in increased identification accuracy and decreased latency of identification when compared to stimuli varying on only one dimension. The advantages attributable to redundant coding are referred to as redundancy gain and have been found for a variety of stimulus dimension combinations, including the use of hue or color as one of the dimensions. Factors that have affected redundancy gain include the discriminability of the levels of one stimulus dimension and the level of stimulus-to-response association. The results demonstrated that response time is in part a function of familiarity, but no effect of redundant color coding was demonstrated. Implications of research on coding in identification tasks for display design are discussed.

1.0 INTRODUCTION

Researchers in both basic and applied areas see color as having a place of importance and privilege in the hierarchy of sensory events (Stokes & Wickens, 1988; Christ, 1975, 1984; Grether, 1972; Garner, 1970). Examples of the important role of color include the observations that perception of color is an essential part of our perception of form (Livingstone & Hubel, 1987), and that color is relatively well discriminated by human vision (Attneave, 1959). When color is used as a means of communicating information, it provides distinct advantages over other forms of representation. Under certain conditions, color coding results in significant improvement in search times (Green & Anderson, 1956; Treisman & Gelade, 1980; Carter, 1982), results in relatively better performance than pattern coding when extracting information from graphic displays (Hoadley, 1990), and provides an efficient cue for selective attention (VonWright, 1970; Foster & Bruce, 1982). As a result of the important role of color in vision and the impressive effects of using color in enhancing performance, color is frequently requested and recommended for visual display coding schemes (Gilmore, 1985, pg. 176-198; Schulze, 1985, pg. 4-3; Krebs, Wolf, & Sandvig, 1978, pg. 5-8, 134-152).

By contrast, it has been reported that under some conditions, color has either no effect or a detrimental effect on performance (Zwaga and Duijnhouwer, 1984; Kanarick and Petersen, 1971). Determining the contribution of color coding is particularly problematic when an identification task is involved because of the difficulty defining the parameters affecting identification. In an effort to clarify some of the relationships between color and other parameters as they affect identification performance, I have proposed a series of questions regarding the parameters that may be involved and attempted to either exclude or define the role of specific parameters. This process includes both inferences drawn from previous research and new research presented here.

1.1 Identification and processing capacity limits

Identification answers questions of what. In identification, the observer encodes information about an external object and categorizes that information. Performance in an identification task is typically a measure of the observer's ability to correctly associate the object with a preassigned response such as naming the object or pressing a key corresponding to the object. Identification has been shown both to be less accurate and take more time than either search or discrimination. Identification differs from search in that in identification, the observer knows where the object will be and typically is only examining one object at a time (in search, the observer is told what to look for, but is unsure of where the object is). Identification differs from discrimination in that in a discrimination task, the objects in question are shown simultaneously while, in identification, the observer must retain in memory the relevant qualities of the object.

Identification tasks are adversely affected by increasing the amount of information presented to the observer. As the number of possible objects increases, the person observing one object will be less certain which of the possible set occurred. Using the example of audition, Fitts and Posner (1967) point out that when a listener is asked to make comparative judgments (is tone i the same as tone j?), the listener is capable of discriminating in excess of a hundred tones. When the listener is presented with only one tone from a set and asked to identify the tone, the listener is capable of accurately identifying an average of only six different tones. Obviously, discrimination is a much different task than identification and identification is relatively limited considering the great acuity demonstrated in discrimination tasks. Similar findings exist in the visual realm (e.g., identification of hues is limited to 9 hues) and in general, humans average being able to identify in the range of 7 (plus or minus 2) values in a given stimulus continuum (Miller, 1956; Attneave, 1959).

1.2 Redundancy gain from multidimensional stimuli

In an effort to explore the role of the stimulus in identification accuracy, Eriksen and Hake (1955) examined the role of stimulus dimensionality on performance. Previous studies examined stimuli that appeared to vary on only one continuum or dimension, and demonstrated limited identification capacity. In daily experience, stimuli typically differ on many dimensions and this additional differentiation can lead to improved identification performance, especially if the values in each dimension are perfectly correlated or redundant. For example, perfect redundancy would be present in a collection of fruits containing apples that are always red, oranges that are always orange and bananas that are always yellow. Eriksen and Hake selected twenty values each of size and hue, and 17 values of brightness. Observers were required to respond with a number from one to 20 or one to 17 as assigned to the stimulus values. Consistent with expectations regarding identification judgments on size, hue, and brightness, observers were only able to correctly identify seven, eight, and five stimuli from each continuum, respectively. When the dimensions were redundantly combined in pairs, correct identification rose to 12 stimuli for size-hue, eight for size-brightness, and 14 for hue-brightness. Redundant combinations of all three dimensions resulted in 17 identifiable stimuli. Similar findings have been demonstrated for combinations of vertical and horizontal position, tone and loudness in audition, and the saltiness and sweetness of taste (Miller, 1956).

In addition to demonstrating increased accuracy of identification as a result of redundant coding, other studies demonstrated shorter response latency for redundant, multidimensional objects than for unidimensional objects. Garner and Felfoldy (1970) compared response latency for stimuli varying on one dimension with response latency for stimuli varying redundantly on two dimensions and stimuli varying orthogonally on two dimensions. The stimuli consisted of colored squares that varied on one of two levels of either brightness or saturation in the unidimensional condition. In the redundant, multidimensional condition, one stimulus consisted of brightness and saturation levels 1 and the other stimulus consisted of brightness and saturation levels 2. In the orthogonal, multidimensional condition, both levels of brightness were combined with both levels of saturation. A significant performance advantage for the redundant pairing of saturation and brightness was found (see Figure 1, panel 1). The advantage was referred to as a redundancy gain and points to stimulus dimensionality as a primary parameter affecting identification performance. At the most basic level, studies on limitations of processing and redundancy gain have demonstrated that increasing dimensionality improves performance, and particularly, redundant hue improves performance. The resulting expectation is that redundant color coding in information displays will always improve performance.

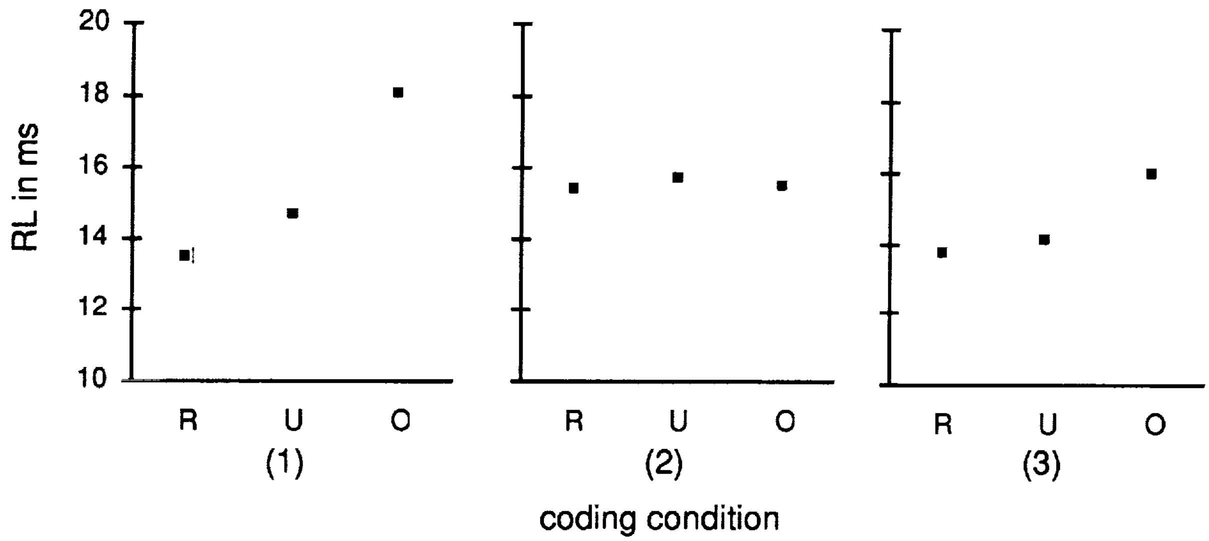

Figure 1. Graphs based on results from Garner and Felfoldy (1970). Response latency (RL)is shown as a function of redundant (R), unidimensional (U), and orthogonal (O) coding for responses to the dimensions brightness and saturation in a single stimulus (1), in adjacent stimuli (2), and with increased discriminability on either dimension (3).

1.3 Robustness of redundancy gain

The question arises as to the robustness of redundancy gain and, for the primary interest of this article, the robustness of the finding of redundancy gain using color as the redundant dimension. The first part of the question can be answered by referring again to Garner and Felfoldy (1970). When the task of identifying brightness and saturation described above was modified such that brightness was represented in one square and saturation was represented in an adjacent square, the advantage associated with redundant coding was lost (see Figure 1, panel 2). With regard to the use of color, Gottwald and

Garner (1972) examined performance on combinations of color and shape and found no evidence for redundancy gain.

A number of other studies have examined the effect of color as a redundant dimension and the varied results demonstrate the difficulty in assessing the role of color in identification performance. In one such study, Luder and Barber (1984) used a fuel system monitoring task to compare performance on displays coded only by shape to those coded redundantly with shape and color. Both a search and an identification task were performed. In each case, the subject was instructed to verify the presence of a specific valve state. In the search task, the position of the valve was not provided. In the identification task, the subject was told a specific valve to check. The size of the display was also varied (5 or 9 valves). The data showed that while color seemed to negate the adverse effect of display size resulting in improved performance for search, it also made identification on the small display as poor as identification on the large display (see Figure 2). Another interpretation is that color enhanced the search task and that set size and color coding have no interesting effects on identification. In either case, the advantage gained through color coding in the search task does not carry over to the identification task.

Zwaga and Duijnhouwer (1984) reported no advantage for color coding for identification in a study comparing shape, color, and redundant pairing of shape and color in a task where subjects were told to report the value of a specific type in a system flow diagram. The five types were coded with shape, color or a shape-color combination but the code did not provide information regarding the value to be identified. Therefore, color provides information aiding search, not identification.

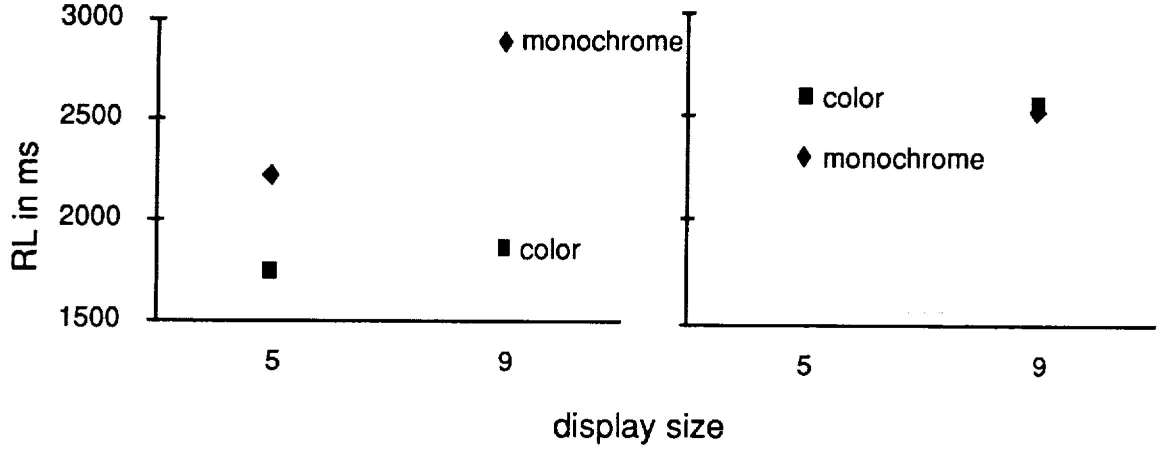

Figure 2. Graphs based on results from Luder and Barber (1984). RLas a function of task (search or identification), display size (5 or 9), and display coding (redundant color or monochrome).

Kanarick and Petersen (1971) examined the relative advantage of number, color, and redundant color-number codes in a monitoring task that included reporting the identity of one of 10 instrument positions. While the complexity of the research design (the variable payoff value is nested at only one level of a second variable, the payoff ratio, both being within subjects, while the three coding variables are between subjects) and the failure to report the degrees of freedom associated with the analysis make it somewhat difficult to interpret the results of this study, it is clear that subject's performance is best in the number only task followed by number-color and color only, respectively, and there is no distinct advantage for redundant coding of color and number. MacDonald and Cole (1988) examined the effect of redundant color coding on operator performance in monitoring flight control displays while the operator concurrently performed a tracking task. The stated variables of interest were color versus monochrome displays, display complexity, and accuracy of a statement regarding the display. The description of the experimental design is unclear as to whether all levels of complexity occur at all levels of the other variables and an additional variable task type is introduced. Coupled with the consistent use of what appears to be a pooled error term in what is stated to be a split-plot design which presents the possibility that significance reported has been overestimated, the results of this study are difficult to interpret.

Keister (1981) compared redundant color code to no color code as a within-subjects factor and reported significant interactions between the type of code and the order in which the subjects were tested on the code types. In this within-subjects design, the replications consist of alternations of a the color-coding factor (color blocks alternated randomly or in a latin square with no color blocks). The order in which tasks are performed can result in the subjects adopting processing and response strategies and carrying the strategies to the next block of trials in which the strategy is inappropriate (Poulton, 1982). One can imagine that a subject who starts the task and develops some level of skill on no-color trials may view the introduction of color as either uninteresting or at worst interferring. On the other hand, a subject starting with color trials may find the absence of color, which the experimental instructions no doubt emphasized as important, distracting. Since main effects are uninterpretable when there are significant interactions that include a confounded variable, attribution of significance to the use of color coding cannot be made in this study.

Calhoun and Herron (1981) also examined the effects of color versus no color as a within-subjects factor in comparing CRT displays to conventional aviation instrumentation, again introducing the order effects issue. The significance of the interaction of the order effect and other experimental variables were not reported, thereby leaving the results regarding the effect of color code uninterpretable.

1.4 Determining factors in redundancy gain

Results from the experiments described above, while attempting to nail down the value of redundant color coding, do not provide a strong arguement for or against color coding in identification tasks. Perhaps worse, they make it difficult to develop a strategic plan of circumstances under which color coding might be valuable. We now ask ourselves, should the idea of redundant coding for identification be abandoned altogether or is it possible to define conditions under which identification is enhanced by color coding? In an effort to salvage some advantage, we must explore the redundancy gain phenomenon and attempt to define those conditions that control redundancy gain.

To this end, an initial point of interest is whether the redundant coding of stimuli improves encoding at the perceptual level. In essence, does a redundant multidimensional stimulus give the observer a better image in working memory? Garner and Creelman (1964) examined this question by varying the exposure duration of the stimuli in an experiment essentially identical to Eriksen and Hake's (1955) study (described in section 1.2), but varying only hue and size. Two stimulus exposure durations (40 ms and 100 ms) were selected based on previous research in which the briefer duration was shown to significantly impair performance. The impairment was attributed to degradation of the encoded image of the stimulus. When performance on unidimensional and redundant multidimensional stimuli was compared, the redundant stimulus set continued to be more accurately identified, irrespective of exposure duration. This finding suggests that the advantage gained by redundancy is not a result of a better image and suggests that the effects involve some higher level of perceptual or cognitive analysis.

A second question that can be asked attempts to look higher on the perceptual path. A basic precondition for identification is that stimuli be discriminable. In a redundant stimulus set, could the relative discriminability of one dimension affect redundancy gain? Garner and Felfoldy (1970) examined this question by varying the discriminability of one or the other aspect of the brightness-saturation stimuli. As previously stated, redundancy gain is described as an advantage for redundantly-paired dimensions over unidimensional stimuli but, in a second experiment when the difference between the values on the saturation level or brightness level were increased, performance on the unidimensional stimuli was equivalent to that on the redundant pair (see Figure 1, panel 3). Equivalent performance between the two conditions suggests that heightened discriminability results not only in performance equal to redundant coding, but can also reduce the adverse effects of orthogonal coding.

The elimination of redundancy gain by increasing stimulus discriminability suggests that redundancy gain is a phenomenon that occurs when the task is affected by the processing limitations of the observer. For this hypothesis to be further supported, other tasks that show varying processing limitations would have to be tested.

Contrary to the evidence showing that processing speed and accuracy for identification are limited to 7 values, processing some types of information is relatively unlimited. For instance, the identification of numbers or alphabetic characters is relatively unaffected by increases in the set of possible values (Mowbray, 1960). Fitts and Switzer (1962) examined this phenomenon and attributed it to the overlearned association between the stimulus (numeric or alphabetic character shapes) and the response (reporting the character name). To answer the question as to whether or not an overlearned Stimulus-Response (S-R) association results in elimination of the limits on identification processing, Fitts and Switzer compared identification performance for a large familiar number set (numbers 1-8), with a small familiar number set (numbers 1,2), and a small unfamiliar number set (numbers 2,7). Responses to the small unfamiliar set took almost as much time as the large familiar set in the first session and almost as little time as the small familiar set by the last session. This result is taken to show an inability of the subject to recognize that there are only two possible outcomes in the small unfamiliar set, responding as if the set was larger. After practice the subject adjusted expectation to the small unfamiliar set and performed more in keeping with the set size. In this case, learning acted to reduce processing limitations in much the same way as redundant color coding or heightened discriminability in the studies of Garner and Felfoldy (1970).

1.5 A strategy for examining the effects of S-R overlearning on redundancy gain

Using the methodology of Fitts and Switzer, the question as to whether redundancy gain can occur in a relatively unlimited task can be asked experimentally. When trying to examine the relationship between processing limitations and redundancy gain, there must be both unlimited and limited tasks. The familiar set of numbers is a highly practiced set for which identification is relatively unlimited. The unfamiliar number set is a set in which identification has been demonstrated to be limited relative to a familiar set of the same size.

In the present research, the hypothesis that redundant coding enhances performance only in limited tasks was examined by comparing performance on redundantly color coded number sets to monochrome number sets using both familiar and unfamiliar number sets. Predictions hypothesizing an interaction between coding and familiarity are presented in Figure 3. Redundant color-number coding, represented by the solid shapes, would not be expected to differ from a number-only display, represented by the open shapes, in the large familiar (LF) and small familiar (SF) sets because extensive learning of the S-R association has already eliminated much of the limitation on responding. Redundant color-number coding would have an opportunity to effect the small unfamiliar set (SU) in much the same way as redundancy improved performance prior to the introduction of more discriminable stimuli in Garner and Felfoldy (1970), since the strong S-R association and expectation of the stimulus set is not yet established.

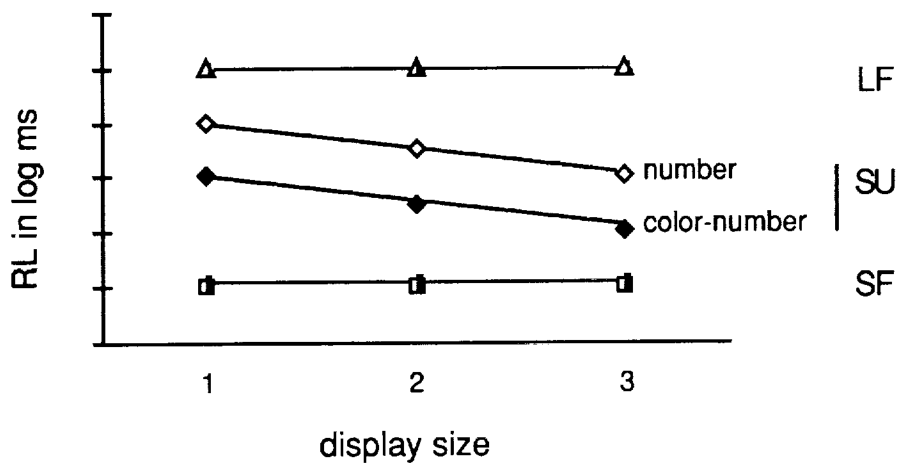

Figure 3. Predicted outcomes for the effects of coding and number set over three sessions of trials on RL. Filled shapes represent the color-number coded trials and unfilled shapes the number-only trials. The sets LF, SU, and SF are represented by the triangles, diamonds, and squares, respectively.

2.0 METHOD

2.1 Apparatus

The stimuli were presented on a Nanao Flexscan cathode ray tube monitor controlled by an IBM XT personal computer with millisecond-level timing of responses and control of stimulus presentation. The subjects sat approximately 46 cm. from the screen. The stimuli consisted of integers from the standard IBM character set (3 mm x 4 mm) presented in the center of a monitor surrounded by a double bordered rectangular frame (14 mm x 17 mm). The display background was black and the characters were white. The responses were taken from keypresses at the number key pad of the standard IBM keyboard.

2.2 Subjects

Twenty four members of the Lockheed Engineering and Sciences Human Factors Department staff were assigned at random to either the color or no color condition.

2.3 Experimental design and procedure

A split-plot design was employed with subjects randomly assigned to the between-subjects variables color (color-number versus number-only) and order of presentation of the number sets (six possible orders), and the within subjects variables number set (large familiar [LF], small familiar [SF], and small unfamiliar [SU]), and sessions (three sessions). The color-number condition was between subjects to eliminate possible carryover effects from one condition to the other. The number sets were presented in blocks. The order of the number sets was counterbalanced across subjects to control for any order effect and allowing for analysis of the contribution of order to the results. Within each block, the subject performed three sessions of each set. The subjects responded by pressing on the number keypad the number corresponding to the stimulus. The bottom row of keys (1,2,3) was used as the home row so that each number set had one key (2) in common that also did not require movement from the home row. This controlled for motor movement differences between responses to the number sets. Both response latency (RL) to the identification of the number 2 and accuracy of responding to the number were recorded.

The subjects were trained to use the keypad in a separate task prior to each block of trials. The instructions presented prior to the experimental trials described the 1:1 relationship between color and number to subjects in the color-number condition, and emphasized speed and accuracy. Prior to starting the trials and after every 8 trials, the number set (with the corresponding colors in the color-number condition) was displayed on screen. The subject initiated further trials from this display and so was able to review the number set (and color mappings in the color-number condition) at regular intervals. Between the number set displays, the start of a trial was controlled by the program. A trial consisted of presenting a white, bordered rectangle midscreen. After 1000 ms, the target number appeared in the center of the rectangle. In the number-only trials, the border was always white while in the color-number trials the border changed to the color assigned to the number when the number appeared. When the subject responded, the number and rectangle were briefly masked, after which the empty, white, bordered rectangle returned. Incorrect responses were signaled by a beep from the computer The subject was required to respond within 5 seconds. Failure to do so resulted in a warning beep and the computer proceeded to the next trial. Missed trials were added to the end of the session. Sessions consisted of 40 trials for each number in the set resulting in 320 total trials for the larger set (8 numbers x 40 trials/number) and 80 trials for the small sets (2 numbers x 40 trials/number). The first session in each block included 24 practice trials following the same procedure as the regular trials. Practice trials were not included in the analysis. The order of presentation of the numbers in the set was randomized within each session.

In the LF set, the numbers 1 through 8 were assigned magenta, blue, cyan, green, yellow, brown, red, and gray, respectively. Assignment of color to the SU and SF sets ensured that the colors used for the 2,7 set were not included in the 1,2 set for that subject (SU set: 2 was cyan or yellow , 7 was brown or gray, SF set: 1 was magenta, blue, or green, 2 was blue, yellow, or red).

3.0 RESULTS

On average, the accuracy of responding exceeded 98% for each point of observation and demonstrated no particular pattern; therefore, no further analysis of accuracy was performed.

The RT data were analyzed using a split-plot, repeated measures design in the general linear models procedure (GLM) of SAS (1985). The between-subjects variables were color and order. The within-subjects variables were number set and session. The results are provided in Table 1 and pictured graphically in Figure 4. Recognizing the skewed nature of reaction time distributions, analysis was performed on the mean of the logarithms of the RLs. The open shapes represent the observed mean log RL for subjects in the number-only trials and the filled shapes represent the observed mean log RLs for color-number trials. The fitted lines represent the best fitting linear model, which contained significant effects of number set, session, and the number set by session interaction.

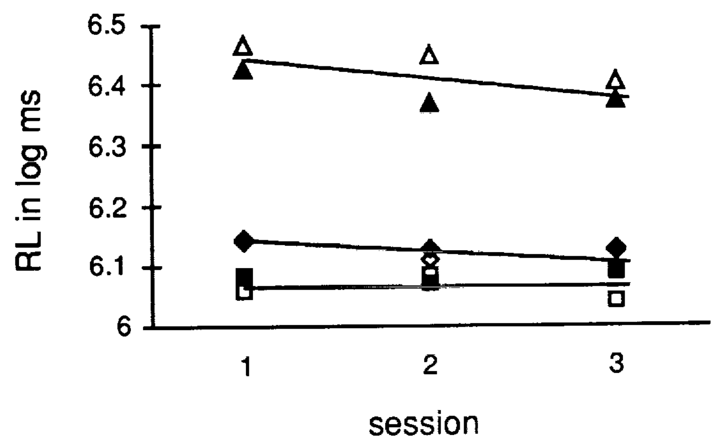

Figure 3. Mean log RLs as a function of color condition, number set and session. Filled shapes represent observations for color-number coded trials and unfilled shapes the number-only trials. The sets LF, SU, and SF are represented by the triangles, diamonds, and squares, respectively. The best fitting model, session, number-set, and session by number-set interaction is represented by the solid lines.

Table 1. Summary of analysis of variance for color (c), order (o), number set (n),and session (s). Subjects within color and group are assigned to appropriate error terms.

	with order				without order			
source	df	ss	F	p>F	df	ss	F	p>F
c	1	0.00	0.06	0.82	1	0.00	0.05	0.82
o	5	0.32	1.11	0.40				
cxo	5	0.32	1.11	0.40				
error	12	0.69			22	1.33		
n	2	4.86	170.77	0.00*	2	4.86	202.86	0.00*
nxc	2	0.05	1.86	0.18	2	0.05	2.22	0.12
nxo	10	0.07	0.48	0.89				
nxcxo	10	0.12	0.82	0.61				
error	24	0.34			44	0.53		
s	2	0.07	4.97	0.02*	2	0.07	4.14	0.02*
sxc	2	0.03	1.82	0.18	2	0.03	1.52	0.23
sxo	10	0.08	1.08	0.41				
sxcxo	10	0.13	1.08	0.11				
error	24	0.18	1.81		44	0.39		
nxs	4	0.02	2.80	0.04*	4	0.02	2.91	0.03*
nxsxc	4	0.01	1.44	0.23	4	0.01	1.50	0.21
nxsxo	20	0.04	1.05	0.43				
nxsxcxo	20	0.03	0.78	0.72				
error	48	0.09			88	0.16		

Performance was found to be dependent on number set, with RT decreasing over sessions. The performance on the number sets was consistent with the findings of Fitts and Switzer (1962), with LF taking the most time followed by SU and then SF. Contrasts between the SU and LF sets, and between the SU and SF sets showed performance on the SU set to be reliably different from performance on the other two sets ($F[1,22]=166.51$, $p=.0001$ and $F[1,22]=21.92$, $p=.0001$, respectively). Polynomial contrasts among the sessions showed that performance improved over sessions in a linear fashion ($F[1,22]=5.73$, $p=.0256$), with no higher order trend ($F[1,22]=.49$, $p=.4902$). The data also showed that the change in performance over sessions differed depending on the number set (number set by session interaction). No other significant effects were found, including no difference between the color-number and number-only conditions, and no main effect of order or interaction between order and other factor.

To further clarify the number set by session interaction, analysis of the session trend at each number set (with color collapsed) was performed. For the LF number set, there was a improvement in performance over sessions ($F[1,23]=11.31$, $p=.0027$) while data for the SU set ($F[1,23]=.91$, $p=.3494$) and the SF set ($F[1,23]=.34$, $p=5660$) showed no change. The lack of improvement in the SF set is consistent with an overlearned task, but similar performance would have been expected in the LF set and an improvement in performance would have been expected in the SU set.

4.0 DISCUSSION

The present research replicated that of Fitts and Switzer (1962) in that both demonstrated significant differences in response time attributable to the subject's familiarity with the number set. In the present research, responding to the unfamiliar 2,7 set took longer than the equal sized but familiar 1,2 set.

Contrary to expectations, the interaction between number set and color code that would have indicated redundancy gain did not occur. The strategy of the research design was to provide an unfamiliar number identification task that would allow redundancy to exert some positive influence on response latency. The significant effects of the other variables, number set and session, argue against a position that the failure to find redundancy gain was due to insufficient experimental control. The failure to find an effect for redundant coding in the limited 2,7 task suggests that the conditions under which redundancy gain occurs require more than simply limited performance on the part of the observer.

In conclusion, the present research supports previous studies that have reported the failure of a redundant color-number code to enhance performance in the identification of highly learned codes, such as numbers. While research consistently shows the benefits of color for discriminating between objects presented simultaneously and for the coding of search tasks, there is no consistent evidence of improved performance when color is used to redundantly code values that are readily identified. In the design of information displays, color should be used to enhance perception of form, or to enhance search task performance rather than using color for redundant coding in identification tasks. For example, if a user's task includes rapidly locating a general status indicator across a variety of displays (search) and inputting the value of a status indicator as part of system control, a performance advantage would be expected for color coding the location of the general status indicator while no improvement would be expected from color coding the indicator values.

5.0 ACKNOWLEDGMENTS

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13. ABSTRACT *(Maximum 200 words)*
The possibility of finding redundancy gains with overlearned tasks was examined using a paradigm varying familiarity with the stimulus set. Redundant coding in a multidimensional stimulus has been demonstrated to result in increased identification accuracy and decreased latency of identification when compared to stimuli varying on only one dimension. The advantages attributable to redundant coding are referred to as redundancy gain and have been found for a variety of stimulus dimension combinations, including the use of hue or color as one of the dimensions. Factors that have affected redundancy gain include the discriminability of the levels of one stimulus dimension and the level of stimulus-to-response association. The results demonstrated that response time is in part a function of familiarity, but no effect of redundant color coding was demonstrated. Implications of research on coding in identification tasks for display design are discussed.

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