Research Article

REPRESENTATION OF COLORS IN THE BLIND, COLOR-BLIND, AND NORMALLY SIGHTED

Roger N. Shepard[1] and Lynn A. Cooper[2]

[1]*Stanford University and* [2]*Columbia University*

Abstract—*Human adults with normal vision, with three types of color-blindness, or with complete absence of vision since birth rank-ordered the similarities of all pairs of colors corresponding to nine hue names. When presented with the names only, subjects with any color vision produced rankings for which multidimensional scaling yielded Newton's color circle. When subjects were presented with the colors themselves, the recovered color circle remained the same for the normally sighted but collapsed along the red-green dimension for the color-blind. Based on their rankings by color names, the totally blind subjects all fell outside the range of the color-normal subjects but partly overlapped the color-deficient subjects; a rare rod monochromat roughly approximated the color-normal subjects. These results, along with those of Marmor (1978) and Izmailov and Sokolov (this issue), suggest how visual experience, language, and innate structure contribute to the mental representation of colors.*

Colors, subjectively so simple and vivid and yet objectively so difficult to describe or to reduce to physical terms, have long raised puzzling questions for scientists, philosophers, and laypersons: Do colors exist in the external world, or only in the mind of the beholder? How do colors appear to color-blind individuals? Does your experience of red have the same subjective quality as my experience of red? What ideas about colors develop in persons who have been totally blind since birth?

Partly motivated by such questions, during 1969 and 1970, we collected similarity data for nine hues around the color circle from people with normal vision, with three types of color-blindness, and with complete absence of vision since birth. In keeping with an ongoing program of research on "second-order isomorphism" between internal representations and the external things they represent (Shepard, 1975, 1978b; Shepard & Chipman, 1970; Shepard, Kilpatric, & Cunningham, 1975), we asked the subjects to judge the similarities of colors when only the names of the colors were presented and (except for the blind subjects) when the corresponding colors themselves were presented. We summarized our results at a scientific meeting (Shepard & Cooper, 1975) and in some published overviews of work on mental representations (Finke & Shepard, 1986, pp. 37-5–37-7; Shepard, 1975, p. 97). With our ensuing engagement in research on mental transformation (reviewed in Cooper & Shepard, 1984; Shepard & Cooper, 1982), however, we never published a full report of our now 20-year-old investigation into the representation of colors.

In the meantime, two studies that complement our work in significant ways have emerged. The first is a follow-up study by Marmor (1978), which presented our nine color words to a larger sample of blind individuals, including cases of late as well as early blindness. The second is an independent Soviet study reported in the accompanying article by Izmailov and Sokolov, in which normally sighted subjects first learned arbitrary associations between artificial words and hues around the color circle and then judged the similarities among the colors when only their newly associated names were presented. This publication of Izmailov and Sokolov's results seemed to us a fitting occasion for a fuller presentation of our own earlier findings, together with some comparisons between our findings, theirs, and those of Marmor.

THE PROBLEM OF COLOR REPRESENTATION

The hues of the rainbow correspond to a one-dimensional continuum of physical wavelengths. Yet the red and violet extremes of this visible continuum appear more like each other than either appears like an intermediate hue (e.g., green). Thus, the physically rectilinear continuum of wavelength gives rise to a psychologically circular continuum of hues—the *color circle* described by Newton (1704). Nonmetric multidimensional scaling, which finds the spatial configuration of points such that stimuli judged to be more similar correspond to points that are closer together (Shepard, 1962a, 1962b; see also Kruskal, 1964a), can recover this color circle merely from a subject's similarity ordering of all pairs of n presented hues (Shepard, 1962b, Fig. 13; Shepard, 1980).

Mixtures of different wavelengths give rise to additional, less saturated colors not falling on the circle of pure spectral hues. Indeed, because the amount of light at each wavelength can be independently varied, the physical degrees of freedom of light are essentially unlimited. Yet, human observers, having only three types of color-sensitive retinal cones, can always match the resulting appearance by adjusting no more than three variables on a suitable color-mixing apparatus—variables corresponding to brightness, hue, and saturation, or, alternatively, to *opponent-process* dimensions of light-versus-dark, blue-versus-yellow, and red-versus-green (Hering, 1878/1964; Hurvich & Jameson, 1957). Multidimensional scaling can also recover the implied three-dimensional color space of the color normal (Indow, 1988; Indow & Kanazawa, 1960; Shepard, 1978a), as well as the differentially compressed or lower dimensional color spaces of the color deficient (Carroll & Chang, 1970b; Wish & Carroll, 1974).

But how are colors represented in individuals who are not actually perceiving those colors but only imagining them? And how are colors represented or imagined in individuals whose visual experience has been impoverished or absent since birth,

Address correspondence to Roger N. Shepard, Department of Psychology, Building 420, Stanford University, Stanford, CA 94305-2130; e-mail: roger@psych.stanford.edu.

as a result of altered or missing retinal receptors? Such questions bear on epistemological debates between empiricist and nativist philosophers. Even Hume departed from the strict empiricist maxim that all ideas initially enter the mind through the senses when he admitted that a person who had experienced all colors "excepting one particular shade of blue" might nevertheless be able to imagine that never-experienced color (Hume, 1739/1896, p. 6).

To investigate the representation of colors in persons with widely differing sensory experiences of colors, we employed a method (introduced by Shepard & Chipman, 1970) in which subjects judge the similarities between stimuli under two conditions: when those stimuli are actually presented and when those stimuli are only named. At about the same time, Fillenbaum and Rapoport (1971; see also Rapoport & Fillenbaum, 1972) presented only the names of colors to normally sighted subjects and, using multidimensional scaling, obtained color circles resembling those obtained by other investigators for physically presented hues (Carroll & Chang, 1970b; Helm, 1964; Indow & Uchizono, 1960; Shepard, 1962b; also Schneider, 1972). Our experiment was, however, the first directly to compare similarity data for color names and for actual colors selected to correspond one-to-one to those same names, and the first to include blind and color-blind subjects, along with the normally sighted.

METHOD

Subjects

We recruited 37 subjects, primarily through notices circulated at Stanford University and through a local agency providing aids for the blind. Based on the responses of the sighted subjects to the test plates in Ishihara (1977), we classified the subjects into six groups: (a) 14 adults with normal trichromatic color vision, (b) 7 with color deficiency of the strong *deutan* type, (c) 4 with color deficiency of the strong *protan* type (see Farnsworth, 1947, and Ishihara, 1977, concerning these two types), (d) 1 with rare monochromatic vision (a female adult with rod vision only, referred to us by Barbara Sakitt), (e) 6 with total blindness since immediately after birth (typically as a result of retrolental fibroplasia), and (f) 5 others with miscellaneous weaker color anomalies, who are not included in the analyses presented here.

Stimuli

As familiar names of spectral hues, we selected the nine words *red, orange, gold, yellow, green, turquoise, blue, violet,* and *purple*. For each of these names, we then selected the *Color-aid* paper that a small preexperimental group of judges with normal color vision most often chose as the best exemplar for that name. Moreover, for the six of our names that qualify as *basic color terms* (Berlin & Kay, 1969)—*red, orange, yellow, green, blue,* and *purple*—the colors we selected fall within the regions of Munsell color space that other normally sighted native speakers of American English have accepted as prototypical exemplars of those colors (Berlin & Kay, 1969, p. 119). The color samples in the *Munsell Book of Color* (1976) that best match our selected red, orange, gold, yellow, green, turquoise, blue, violet, and purple Color-aid papers are designated 5R 4/14, 10R 5/14, 8.75YR 7/14, 2.5Y 8.5/12, 7.5G 4/10, 10BG 5/8, 6.25PB 3/12, 5P 3/8, and 10P 3/10, respectively. These colors necessarily were not equated in lightness; the prototypical color corresponding to *yellow,* for example, is appreciably lighter than the prototypical colors corresponding to *red, green, blue,* or *purple* (Berlin & Kay, 1969, p. 119).

We then prepared four decks, each containing 36 (7.6 cm × 12.7 cm) white cards corresponding to the 36 pairs of distinct colors (randomly assigned to the left and right positions on each card). For a *Colors-only* deck, we mounted on each card (with a separation of 2.5 cm) two 3.8-cm squares cut from the corresponding colored papers. For two *Names-only* decks, we instead typed on each card only the names of the pair of assigned colors—in black letters for the deck to be presented to the sighted subjects and in raised braille characters for the deck to be presented to the blind subjects. For a *Names + Colors* deck, we affixed on each card the two assigned color squares and directly under each color, put the corresponding printed name.

Procedure

Each subject was given a shuffled deck and asked to rearrange the cards until satisfied that all 36 cards were ordered according to the similarity between the two colors displayed or named on each card. All subjects with any color vision did this for the three decks: Names-only, Colors-only, and Names + Colors, in that order. The monochromat did this for just the Names-only and (subsequently) the Names + Colors decks, and the six blind subjects did this for just the braille Names-only deck. Thus, only the Names-only condition was presented to all subjects, and it was always presented first. (Other studies have not found an appreciable effect of order of presentation of perceptual and names-only conditions; see Shepard & Chipman, 1970; Shepard et al., 1975.)

RESULTS

The data for each subject in each condition take the form of a 9 × 9 triangular half-matrix in which each of the 36 cells contains the rank (between 1 and 36) of the similarity of the colors corresponding to the row and column of that cell. The analyses we present are based on 83 such matrices, corresponding to 25 subjects with color vision × 3 conditions, 1 monochromat × 2 conditions, and 6 blind subjects × 1 condition.

Analyses of Correlations Among Subject–Condition Combinations

For initial analyses of the similarities and differences among types of subjects (normal, deutan, protan, monochromat, or blind) and conditions (Names-only, Colors-only, or Names + Colors), we computed an average matrix for each combination of type of subject and condition (without, however, the monochromat's Names + Colors condition, which we added only later). We then computed the product-moment correlation between corresponding cells for each pair of the resulting (3 + 3 + 3 + 1 + 1) matrices, yielding an 11 × 11 symmetric matrix of correlation coefficients.

Application of the hierarchical clustering method HICLUS (Johnson, 1967) to this correlation matrix revealed that the 11 subject–condition combinations fell into three disjoint groups: one for the subjects having any color vision, one for the monochromat, and one for the completely blind subjects. Indeed, regardless of whether names, colors, or names plus colors were presented, all 36 correlations between matrices within the color vision group (ranging from .802 to .989) were larger than any of the 19 correlations between matrices divided between any two of these three groups (ranging from .534 to .796).

Because the similarity rankings fell into these three disjoint groups, nonmetric multidimensional scaling (Kruskal, 1964a, 1964b; Shepard, 1962a, 1962b) yielded a *degeneracy* (see Shepard, 1962b, 1974) in which the 11 subject–condition combinations collapsed onto the vertices of an equilateral triangle, with each of the three groups at a different vertex. Any pattern of individual differences within the color vision group was lost in its collapse to a point. We therefore applied nonmetric multidimensional scaling to just the 9 × 9 correlation matrix remaining after deletion of the rows and columns for the monochromat and for the group of blind subjects.

Figure 1 shows the two-dimensional solution (obtained by the program KYST—see Kruskal, Young, & Seery, 1973; Shepard, 1980, note 21), with the already mentioned hierarchical clustering embedded as a set of nested curves. (The very same clusters emerged from the "maximum" and "minimum" variants of HICLUS—indicating that the obtained clusters are strongly determined by the correlation data.) The number associated with each cluster is the smallest correlation between any two enclosed combinations of subject type and condition. The remaining two, increasingly inclusive clusters (not shown) added, first, the monochromat (with a minimum correlation of .74) and, finally, the blind subjects (with a minimum correlation of .53).

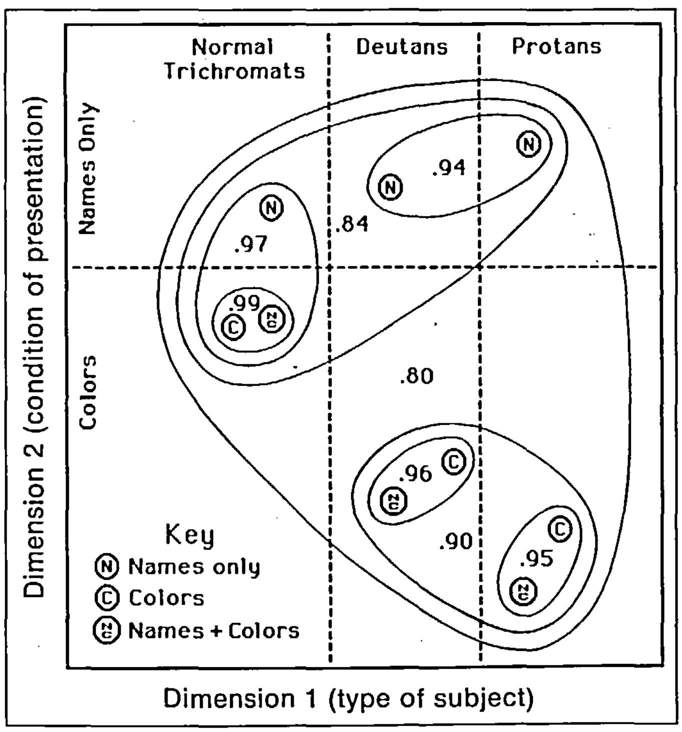

Fig. 1. Nonmetric multidimensional scaling solution, with embedded hierarchical clustering, based on the correlations among the averaged similarity rankings for nine combinations of type of subject (normal, deutan, or protan) and condition of presentation (Names-only, Colors-only, or Names + Colors). The number inscribed within each cluster is the smallest correlation between any two combinations in that cluster.

This two-dimensional scaling solution is nondegenerate, provides a good fit to the correlation data (stress = 8.9%), and is readily interpretable. For the normal trichromats, the three conditions (labeled N, C, and NC in the upper left) all intercorrelate at least .97 and, hence, are tightly clustered. As in similar studies using other stimuli—including visual shapes, spoken words, faces, and odors (e.g., Shepard, 1975, 1978b; Shepard & Chipman, 1970; Shepard et al., 1975)—the similarity comparisons seem to have been based on internal representations that functioned equivalently whether the colors were perceived or only imagined.

As might be expected from the fact that the deutans and protans have a reduced ability to discriminate between reds and greens, their points for the conditions in which the colors were actually presented (C and NC) are far removed from the region of the color-normal subjects. Remarkably, however, when these color-deficient subjects were presented with the names only, their points (N) remained relatively closer to the points for the color-normal subjects. These subjects knew that red and green appear very dissimilar to most people. Yet the proximity of the points labeled NC to those labeled C (rather than to those labeled N) indicates that when the names were presented along with the colors, the color-deficient subjects based their similarity judgments on their immediate visual experience of those colors more than on their knowledge of the relations among those colors for color-normal observers.

Analyses of Similarity Rankings From Subjects With Color Vision

The two-dimensional solutions obtained by separately applying multidimensional scaling (KYST) to the similarity rankings from all subjects in the different subject–condition combinations reinforces this interpretation. On the left in Figure 2, we show the four solutions based on the data from the 14 color-normal subjects (at the far left) and from the 11 color-deficient subjects (in the middle), both for the Names-only condition (above) and for the Colors-only condition (below). In agreement with our interpretation of Figure 1, Newton's color circle clearly emerged for the color-normal subjects in both conditions and (except for a reversal between the two encircled closest neighbors, violet and purple) for the color-deficient subjects in the Names-only condition. Despite their perceptual deficit, the color-deficient subjects have an accurate conceptual representation of the relations among the nine colors, just as the color-normal subjects do. In the Colors-only condition, however, the color circle collapsed for the color-deficient subjects, bringing

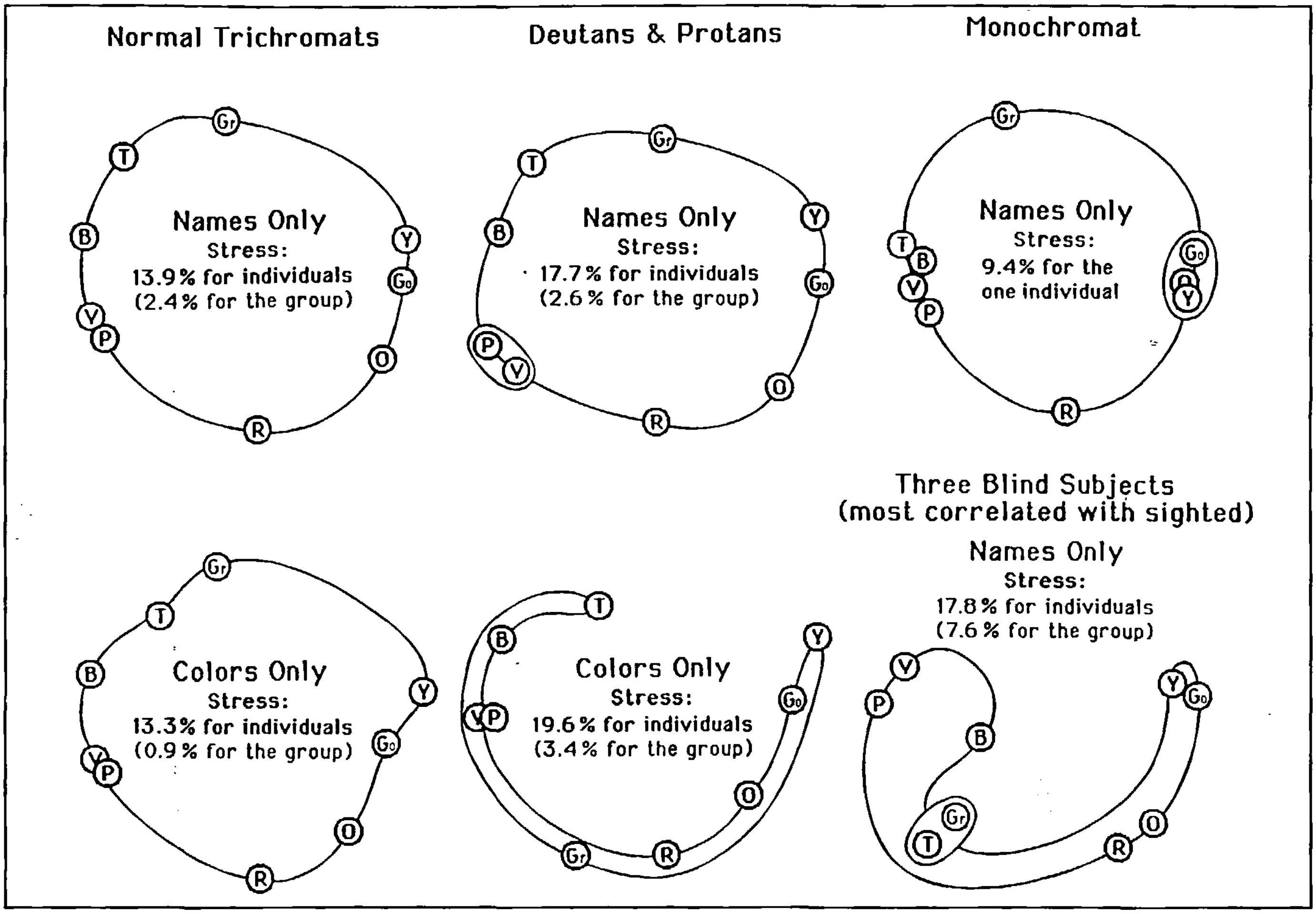

Fig. 2. Nonmetric multidimensional scaling representations for the nine colors—red (R), orange (O), gold (Go), yellow (Y), green (Gr), turquoise (T), blue (B), violet (V), and purple (P)—based on average similarity rankings: (a) for the normal trichromats (left) and the color-deficient subjects (middle) under the Names-only condition (above) and the Colors-only condition (below), (b) for the monochromat under the Names-only condition (upper right), and (c) for the three blind subjects who correlated most highly with the sighted subjects under the Names-only condition (lower right). (Stress Formula 1 was minimized in all cases.) The first stress value given for each group of subjects was computed from the rankings of individual subjects in that group and should be roughly comparable across the groups of different sizes. The second (parenthetical) stress value for each group was computed from the more stable similarities averaged over all subjects in the group as a whole and, hence, tends to be smaller for the larger groups. The smooth curve drawn through the nine points in each solution indicates the degree of approximation to the standard color circle. Points in permuted orders on the curve are encircled.

the red and green sides of the circle together. In fact, such a C-shaped configuration indicates a close approximation to unidimensionality (Shepard, 1974) and hence (if we allow for variation of lightness as well as color) to dichromacy.

INDSCAL Weights for Different Subject–Condition Combinations

To obtain a spatial representation of individual differences that includes the blind subjects and the rod monochromat, we analyzed the similarity matrices for all 32 subjects by the INDSCAL method of multidimensional scaling (Carroll & Chang, 1970a). INDSCAL, being a metric method, uses more than the ordinal properties of the data, but is less susceptible to degeneracy than are nonmetric methods. In addition, INDSCAL estimates weights that (when squared) indicate how much of the variance of each input matrix is explained by each of the orthogonal dimensions of the spatial solution.

For the first of our two such analyses, we computed an average similarity matrix for the six blind subjects, for the single monochromat, and for each combination of type of subject having color vision (normal, deutan, or protan) and condition (Names-only, Colors-only, or Names+Colors). The two-dimensional INDSCAL solution accounted for 88.0% of the variance in the resulting 11 averaged matrices. The nine colors in the group stimulus space formed a color circle (see lower left inset in Fig. 3) resembling the three color circles in the left and top center of Figure 2. Moreover, the horizontal and vertical axes—which in an INDSCAL solution should be interpretable without rotation (Carroll & Chang, 1970a)—were immediately

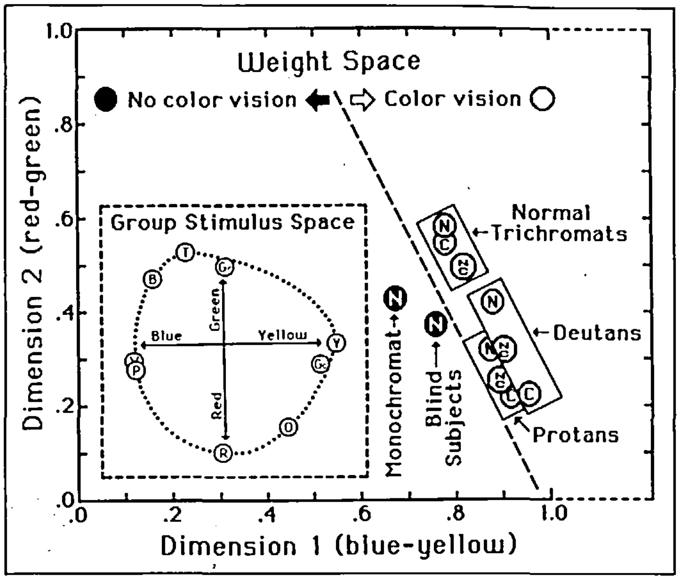

Fig. 3. Weights on Dimension 2 (interpreted as the red-green dimension) plotted against weights on Dimension 1 (interpreted as the blue-yellow dimension) for the 11 combinations of type of subject and condition, from an INDSCAL analysis of the average ranked similarities for those 11 combinations. Subject types with and without color vision are represented by white and black circles, respectively. The inset in the lower left shows the color circle that emerged in the group stimulus space.

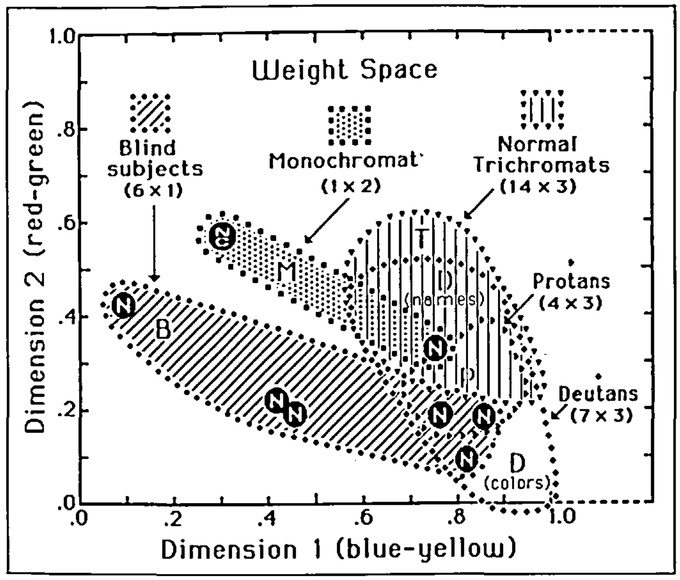

Fig. 4. Weights on Dimension 2 (interpreted as the red-green dimension) plotted against weights on Dimension 1 (interpreted as the blue-yellow dimension) for all 83 combinations of individual subject and condition, from an INDSCAL analysis of the ranked similarities for those 83 combinations. Each dotted convex curve encloses all points for the indicated type of subject. Multiplication of the number of subjects of that type by the number of conditions for that type—the two parenthetically indicated numbers—yields the number of points enclosed in that curve.

identifiable with the blue-yellow and red-green opponent-process dimensions of human color vision (Hering, 1878/1964; Hurvich & Jameson, 1957).

The two-dimensional weight space for the 11 combinations of subject type and condition, which constitutes the main part of Figure 3, is also readily interpretable. The three points for the normal trichromats cluster together in the upper right of the positive quadrant, where both dimensions are heavily weighted. The deutans and the protans are displaced, as expected, in the downward direction of lower weights on the red-green dimension. As in Figure 1, however, the color-deficient subjects remain closer to the color-normal subjects in the Names-only condition than in the other conditions.

As indicated by the slanting broken line, the blind subjects and the monochromat are linearly separable from all points for subjects with color vision (whether normal or deficient), and are closer to the origin (0, 0) at the bottom left corner of the quadrant, where no variance would be accounted for by the color circle. Overall, the variances accounted for were 96% for the normal trichromats, 93% for the deutans, 88% for the protans, 71% for the blind subjects, and 68% for the single monochromat.

Our second INDSCAL analysis was applied to the whole set of 83 individual matrices. The two-dimensional solution accounted for 77% of the variance of these more numerous but individually less reliable matrices. A color circle virtually identical to that shown in the lower left inset in Figure 3 emerged in the group stimulus space, with the horizontal and vertical dimensions again corresponding to the blue-yellow and red-green opponent processes. Figure 4 shows the weight space for the 83 subject–condition combinations. Individual points are plotted only for the six blind subjects and for the monochromat's two conditions (N and NC). The 76 points for subjects with color vision are too crowded to be shown separately, but we indicate the subregions to which they are confined by convex dotted curves that enclose all points for each type of subject.

Again, the normal trichromats all have high weights on both dimensions, while the color-deficient subjects have generally lower weights on the red-green dimension. The individual points are, of course, more scattered here than the points based on averaged matrices in Figure 3. Although the points in the upper portion of the deutan region overlap with the normal trichromat region, these points are from the deutans' Names-only condition, while the points in the lower, nonoverlapping portion of the deutan region are from the conditions in which the colors themselves were present. As before, the protan region has less vertical spread than the deutan region. (The wider separation in Fig. 1 between the colors-present and colors-absent conditions for the protans may reflect differences on other dimensions; see Chang & Carroll, 1980.)

The points for the subjects having no color vision are much more widely scattered. Among the six congenitally blind subjects, three fall far to the left, with greatly reduced weights on the blue-yellow dimension, and with variances accounted for of only 22.9%, 23.0%, and 23.2%; the other three fall within the lower (Colors-only) region of the color-deficient subjects, with variances accounted for of 58.7%, 67.2%, and 70.3%. Even these latter three blind subjects, however, have no overlap with the convex region containing all 42 points for the normal trichromats.

Among the subjects without color vision, only the rod monochromat overlaps the normal trichromats' region—and this occurs only for the monochromat's Names-only condition. The point for her Names + Colors condition is again far to the left. In the face of her own, different sensory experience, when the colors were visually in front of her, the monochromat, like the color-deficient subjects, evidently made little use of the conceptual knowledge she had acquired about the relations among colors.

Analyses of Similarity Rankings From Subjects Without Color Vision

We applied the multidimensional scaling program (KYST), separately, to the average data (a) for the three blind subjects whose INDSCAL weights overlapped those of the sighted subjects, (b) for the three blind subjects whose weights fell outside those of the sighted subjects, (c) for the monochromat under the Names-only condition, and (d) for the monochromat under the Names + Colors condition. The two-dimensional solutions for the two of these four cases (viz., b and d) for which the subjects most differed from subjects with color vision appeared quite chaotic and bore little resemblance to Newton's color circle. Some colors that are very different for the normally sighted were close together (e.g., red and green, in case b; gold and turquoise, or violet and orange, in case d), while some colors that are very similar for the normally sighted were far apart (e.g., purple and violet, in case b; orange and yellow, in case d).

More interpretable are the two solutions, displayed to the far right in Figure 2, for the two of these four cases (viz.; a and c) that were most correlated with data from subjects possessing color vision. The solution for the monochromat in the Names-only condition (upper right) recovers the color circle—but with a nearly degenerate grouping of the nine colors into four groups: red, green, turquoise-through-purple, and yellow-through-orange (with yellow in a permuted position within its encircled group). The solution for the three blind subjects who were most correlated with the sighted subjects (lower right) preserves only a quite deformed vestige of the color circle in which the "warm" colors are on the right, the "cool" colors are on the left, and the red and green sides of the circle are again close together. Possibly, the red-green opposition, which is weak or lacking in the most common (deutan and protan) types of color-blindness, is also the most likely to be weakly instantiated in the higher, representational levels of the brain. (See White, Lockhead, & Evans, 1977, for further support for this possibility.) Still, the three solutions for the Names-only condition in the right and top center of Figure 2 all indicate that some individuals whose color vision has been either deficient or absent since birth can acquire some idea of the relations among colors as experienced by the normally sighted.

DISCUSSION AND CONCLUSIONS

Comparison With the Results of Marmor

Marmor's (1978) follow-up study, although limited to blind and normally sighted subjects and to the Names-only condition, included a larger sample of blind subjects and, also, subjects who had become blind only later in life. The results for her 16 late-blind subjects were intermediate between those for her 16 early-blind and her 16 normally sighted subjects. Apparently, individuals who have become blind, even after having had considerable visual experience, have not assimilated or have not retained the similarity relations among colors as fully as individuals who continue to have sight.

Marmor's relatively large sample of early-blind subjects included some whose multidimensional scaling results approximated Newton's color circle more closely than the results for our six blind subjects. (Compare the quasi-circular configurations on the right in Marmor's Fig. 1 and top right in her Fig. 3 with the distorted configuration in the lower right of our Fig. 2.) Even for Marmor's most successful blind subjects, however, neighboring hues (such as yellow and gold, or violet and purple) were sometimes reversed. Overall, moreover, the multidimensional scaling results indicate just as marked a difference between the blind and sighted subjects in Marmor's study as in ours:

1. The variances accounted for by the two-dimensional INDSCAL solutions (though estimated in different ways in the two studies) were consistently smaller for the early-blind group than for the sighted group—in our study, 71% for the blind versus between 95% and 97% for the normally sighted (depending on the condition of presentation) and, in Marmor's study, 44% for the early blind versus 79% for the normally sighted (and 72% for the late blind).
2. There was almost no overlap, in the two-dimensional INDSCAL weight space, between the weights for the early-blind and the normally sighted subjects. Specifically, the weights for all of our 6 blind subjects fell outside the smallest convex region containing all 42 points for our 14 normally sighted subjects under the different conditions (see our Fig. 4). Similarly, the weights for all but 1 of Marmor's 16 early-blind subjects fell outside the smallest convex region containing all 16 points for her normally sighted subjects (see her Fig. 2).
3. The (stress) measures of departure from good fit of the two-dimensional configurations obtained by nonmetric multidimensional scaling were consistently higher for the early-blind group than for the normally sighted group—in our study, 6% versus 2%, respectively, and, in Marmor's, 13% versus 2%, respectively.
4. The multidimensional scaling configurations for some of the blind subjects bore little resemblance to the color circle. Much as in the solution for our three blind subjects who least correlated with the sighted subjects, in the illustrative solution presented by Marmor (Subject 6 in her Fig. 3), quite similar colors (red and orange, or purple and violet) were far apart, while very dissimilar colors (yellow and purple) were close together.

We are not saying that color relations could not be learned, in the absence of visual experience, by an individual with sufficient motivation and linguistic input about colors. Our monochromat, having vision though no color vision, clearly took a greater interest in colors than did any of our totally blind subjects. (She even claimed she could discriminate colors, though any such discriminations were presumably based on lightnesses or contextual cues.) Over the years, her interest in vision may have led her to pick up, through language, the similarity relations inherent in the color circle. Some of Marmor's 16 early-blind subjects may have had a similarly augmented interest in or exposure to the semantics of color terms. Nevertheless, our results, as well as Marmor's, suggest that the relations among colors are not easily, completely, or precisely mastered in the absence of any direct acquaintance with colors.

Comparison With the Results of Izmailov and Sokolov

Once an internal representation of colors has been established, however, one need not construct a new mental structure from scratch in order to make similarity judgments but can simply reinterpret and use the already existing mental structure. Such a possibility is suggested, for example, by an early experiment by Phillips (1958). English-speaking adults first learned arbitrary pairings between five Turkish words and five Munsell grays varying only in lightness. Then, following the pairing of a loud tone with the word associated with the darkest shade of gray, the strength of the conditioned galvanic skin response (GSR) was found to be greater for those words that had previously been associated with more similar (i.e., darker) shades of gray.

Izmailov and Sokolov (this issue) provide a fuller and more quantitative demonstration, using judged similarity (rather than generalized GSR), a much greater variety of colors, and multidimensional scaling. After having their Russian subjects learn arbitrary pairings between 20 colors and 20 artificial color names, they presented each pair of the artificial color names only and had the subjects rate the degree of difference between the two corresponding colors. Following a small amount of color–word learning, similarity ratings revealed a crude grouping of the words into four clusters—somewhat, perhaps, as the solution for our monochromat (top right of our Fig. 2) revealed four clusters. Then, following more extensive color–word learning, the full color circle emerged. A significant advantage of using words that had been arbitrarily associated with colors was that positions around the color circle could be filled in between hues with existing names (e.g., between the nine hues corresponding to our nine familiar English color names).

Conclusions

The perception and representation of colors does not depend only on color-sensitive retinal receptors. It also depends on the higher level neural networks required to achieve an internal representation of colors that captures what has been most color constant and biologically significant in the light scattered to our eyes from external objects over evolutionary history (Shepard, 1991). An understanding of the relations among surface colors (as experienced by color-normal observers) tends to develop even in individuals who have never directly experienced the full range of colors, as in our protans, deutans, and monochromat. Such individuals may achieve this understanding, in part, by virtue of an inborn opponent-process system (and associated hue circle) for representing color (in much the way proposed for sighted individuals; see Miller & Johnson-Laird, 1976, pp. 344–346).

If so, such an understanding need not be purely conceptual, however. Suggestively, one of our strong protan subjects told us that his mental images of red and green were much more vivid and different from each other than any color sensations he experiences when actually looking at red or green objects. Suggestively, too, the spinning black-and-white pattern on a Benham disk, which produces illusory sensations of desaturated red, yellow, green, and blue in normal observers, has led color-blind observers to say such things as "That line is definitely colored, but I don't know what to call it" and "Those lines are greener than grass" (White et al., 1977, p. 523).

The possibility remains, however, that the various degrees of understanding of color relations demonstrated by our blind and color-blind subjects arose primarily from their years of learning the pairwise relations between colors through language. Yet, despite a lifetime of linguistic exposure, individuals who have been totally blind since birth seem not to develop, fully, the remarkably consistent representation that is characteristic of all sighted individuals. Surely, the neural circuitry for the normal representation of colors is to some extent innate, but the development of that circuitry and of its connections with linguistic input may be reduced in the total absence of any sensory grounding of that circuitry in the external world.

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