The Perception of Moderate and Large Color Differences in Photographic Prints: An Evaluation of Five Color-Difference Equations

by

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Approved:

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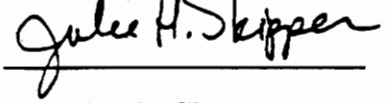

Julie H. Skipper

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ABSTRACT

The task of determining which of many available color-difference formulae is appropriate for any give application can be arduous. Researchers and practitioners alike are faced with the selection of one formula which best describes perceived color differences under conditions in which the equation is to be employed. The idea that one equation can be formulated which takes into consideration all factors affecting perceived color difference has yet to be realized, and perhaps never will. As a result, an "every man for himself" approach has developed. Yet, color-difference equations are continually being applied to conditions without empirical evidence to support their use.

While the 1976 CIELAB Color Difference Equation has been applied for some time in the photographic industry, its use in describing the perceived magnitude of large color differences in photographic prints has not been

validated. Furthermore, a good deal of research has suggested that the CIELAB equation is not applicable under numerous conditions of color-difference assessment. Nonetheless, the results of the study reported here support the use of CIELAB over four other formulae (CIELUV, CMC (1:1), Richter, and Yu´v´) for describing perceived color differences in photographic prints. CIELAB produced moderate correlations for both experienced and non-experienced color judges over the range of color space examined.

The results of this work support the use of the 1976 CIELAB Color Difference Equation for describing the perceived magnitude of moderate and large color differences in photographic prints.

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OBJECTIVE

The objective of this thesis is to investigate the perception of moderate and large color differences in photographic prints. This objective is achieved, in part, by correlating magnitudes of perceived color differences with values calculated using five established color-difference equations. Ultimately, one equation is determined to be best in relating moderate and large color differences with perceived magnitude of color difference for photographic prints.

INTRODUCTION

An elusive goal which has challenged color scientists and psychologists alike for over 50 years has been the pursuit of an equation to quantitatively define a perceptually uniform color space. Work has concentrated on generating a model which represents the magnitude of perceived difference between colors as a function of their physical distance separation from one another in this space. Ever since the pioneering work of MacAdam (1942, 1943), numerous color-matching and color-difference experiments have been conducted. However, a suitable equation to accurately describe results obtained from these various psychophysical experiments still eludes researchers.

MacAdam demonstrated how man's ability to discriminate small color differences varies throughout the color spectrum. With this type of fundamental information regarding human color perception, the

establishment of a perceptually uniform color space has been attempted. In a truly uniform color space, each point represents one and only one color. The spacing of all points must be uniform such that the physical distance between any two is proportional to the perceived size of the color difference represented by those two points (Judd, 1967). Beginning with the work of the Optical Society of America Committee on Uniform Color Scales in 1948, repeated modifications and transformations to established color spaces has yet to result in one formula to accurately describe the non-uniform nature of color-difference perception for various applications. As a result, researchers are left to decide which of many available color-difference formulae best describes the outcome for any given experimental situation.

Formulae which in the past have been adopted by the CIE (International Commission on Illumination) have not necessarily proved successful in field application. These formulae have, for the most part, been based upon experimental data at threshold levels and obtained in laboratory settings. However, the application of these formulae is generally conducted in less than ideal settings outside the laboratory. In practice, the importance of most formulae for industrial applications is in defining a point somewhere between what is a perceivable color difference and an unacceptable difference. As a result, it is estimated that as many as 20 color-difference formulae have at one time been in use by different industries.

The majority of color-difference formulae are based upon the same type of fundamental research as that of MacAdam (1942), though formulae vary from one another in their weighting of physical attributes used in measuring color. It is known that certain attributes might play greater roles in determining

the perception of color depending upon the application and viewing conditions. As a result, those who use color-difference formulae often adjust or develop formulae to meet applications and conditions of interest. Quite often the decision as to which of the many available formulae should be used is based upon familiarity and industrial practice as much as scientific merit (Robertson, 1977). Even the most recently recommended formulae of the CIE were selected from several of similar merit, under various assessment conditions, solely in an attempt to promote some uniformity regarding color measurement (Robertson, 1990).

Over time, various means have been developed which describe perceived color differences both quantitatively and qualitatively. However, virtually all color difference equations employ the same approach. By producing a series of stimuli with known color differences, as determined by one or more previous color-difference formulae, researchers attempt to correlate calculated values of physical difference with perceptual assessments. The conditions under which these assessments are made varies significantly from one evaluation to another. Most work has been conducted in an attempt to address specific applications as opposed to answering global questions regarding perceived color-difference measurement. Therefore, aspects of color-difference perception such as the size and type of the stimuli used, the magnitude of the differences, the methods of assessment, and the viewing conditions have varied greatly. Even if previous work can be found which is comparable to a researcher's conditions of interest, he or she must determine whether acceptable color difference equations were used to evaluate the results.

The idea that one equation might be formulated which takes into consideration all factors influencing perceived color difference has not been realized. As will become evident in the literature survey which follows, the trend which has developed over the past 50 years has been to establish and validate formulae which best suit a particular application or industry. It was therefore the goal of the research presented here to do likewise. The literature survey, experimental results, and conclusions which follow examine issues concerning the perception of moderate and large color differences in photographic prints. Furthermore, this study identifies one of five potential color-difference equations which provides the highest correlation with perceived color differences for a magnitude estimation experiment.

Approach to the Survey of Color-Difference Literature

Given the wealth of literature concerning color spaces, color-difference equations, and color-difference perception, the following approach to surveying the literature was taken. Work is first divided according to the type of stimuli used during the reported investigations. This division resulted in two separate, though certainly not exclusive, classifications, emissive versus reflective stimuli. Because this document addresses concerns of perceived color differences for photographic prints, considerably greater emphasis is placed on the literature concerning reflective stimuli. Issues also addressed include perceived versus acceptable levels of color difference, psychophysical methods of color-difference assessment, and the effect of color-difference magnitude in previous investigations.

Emissive Stimulus Experiments

The use of emissive-type stimuli in experiments has two distinct advantages over reflective stimuli. First, emissive stimuli are continuously variable. Second, emissive stimuli are, in general, easier to generate. An emissive stimulus, which is the use of colored lights as opposed to colored materials, allows the experimenter to vary the desired characteristics on a continuum, while a reflective stimulus requires presentation in discrete units of difference. Furthermore, emissive stimuli often permit the continuous control of stimuli by either the experimenter or the subject.

Most studies which address the perception of small color differences have relied on emissive stimuli. These studies generally have been concerned with establishing the threshold of color-difference perception under a variety of conditions. The ease with which emissive stimuli may be generated lends itself to the sensitive nature of threshold perception. In addition, emissive stimuli usually allow for a larger color gamut than would otherwise be permissible through the use of reflective stimuli (Morely, Munn, and Billmeyer, 1975).

Beginning with the work of MacAdam (1942, 1943), a great deal of research has been concerned with color-difference formulae to describe the perception of small color differences. MacAdam's work formed the foundation of research concerning perceptually uniform color spaces. He did so by describing the non-uniform relationship between perceived color difference and the physical differences of calculated XYZ values.

Large and moderate emissive color differences. The majority of previous research which addresses the assessment of color-difference formulae is based upon threshold performance in color-matching experiments. However, most industrial applications do not require tolerances of threshold level. Furthermore, the perception of large color differences may rely on different mechanisms from that of perception of small color-differences. Wyszecki (1972) reported that the accuracy of color-difference matching was a linear function of the perceptual size of the difference between stimuli. As the magnitude of the color difference decreased, the correlation with reported differences increased. Once the color differences approached zero, reported differences approached those of a color-matching task. Based upon this information, Wyszecki argued that the data from color-matching experiments generally should not be used to predict the perception of large color differences. The author specifically directed this statement toward the use of the data obtained by MacAdam and others for this purpose.

Support for Wyszecki's argument can be found in several articles. Lippert (1984, 1985, 1986) reported that the CIE 1976 Uniform Color Space metrics were ineffective in correlating large color differences (ΔE) with reading times for random numeral strings from a color cathode-ray tube (CRT) display. Lippert therefore proposed two luminance generalized color legibility metrics, wtd. LUV and Yu´v´. Both of the proposed metrics have since been shown to correlate highly with task performance using CRTs (Martel, 1988; Sayer, Sebok, and Snyder; 1990; Schuchard, 1990a). These results support the adoption of the Yu´v´ metric in the American National Standard for Human

Factors Engineering of Visual Display Terminal Workstations (ANSI/HFS 100-1988) (Human Factors Society, 1988).

Stalmeier and de Weert (1988) used a Gestalt formation technique, a unique approach, as a means of evaluating large color differences encountered on color CRTs. They theorized that for the perception of large color differences, deviations would exist from color spaces which had been based on near-threshold experiments (e.g., CIELAB and CIELUV). Therefore, the authors predicted that rescaling of color spaces would have to take place in order for optimized models to conform to the perception of large color differences. While the authors cited similar conclusions drawn by Post, Lippert, and Snyder (1983), they expressed concern that rescaling would in fact have to be established for every experimental condition.

In using the Gestalt formation approach, subjects in Stalmeier and de Weert's experiments did not offer direct color-difference judgements. The stimulus was presented in the form of a Star of David, two overlapping triangles of different color with the overlapping section comprising a third. Subjects were instructed to make forced choice decisions regarding which direction the combined stimulus appeared to point. Because the stimulus was made up of two overlapping triangles with vertical bases, subjects decided which triangle was most easily discerned as a whole. The Gestalt formation of this triangle was assumed to occur for the two colors in the stimulus having the smallest perceivable color difference between them. This study examined both isoluminant and non-isoluminant color sets.

Stalmeier and de Weert used a multidimensional scaling technique to analyze the data. Results were then compared with those predicted by

various color-difference equations. The authors reported that a rescaled version of the CIELUV space, in which v* was divided by a factor of two, produced the highest correlation with the observed data for the isoluminant color set (r = 0.91). For non-isoluminant colors, a rescaled version of CIELUV, similar to the isoluminant equation where L* is a factor of 5 larger than the standard equation, accounted for 76 percent of the variance. However, in concluding remarks the authors stated that they are not optimistic as to whether significant improvements can be made in the search for a uniform color space for large color differences. They stated that given inter-subject variability as well as the variability concerning different experimental conditions, optimal color spaces will vary according to the specifics of the task and conditions.

Reflective Mode Experiments

Until the relatively recent advent of color CRT displays, most research concerning the industrial application of color-difference perception employed reflective stimuli. One advantage reflective type experiments have over emissive type is that once generated the stimuli can be used in numerous studies. This stability permits repeated use of the stimuli while ensuring with relative confidence that no change in the stimulus appearance has occurred. Once an experimenter has completed the painstaking work to create stimuli, stimuli will always be on hand for additional investigations. One additional advantage of colored reflective stimuli is that while they cannot vary on a continuum, they permit the use of certain scaling techniques

which could not otherwise conveniently be used with emissive stimuli (e.g., rank ordering of magnitude difference) (Morely, Munn, and Billmeyer, 1975).

Perceived versus acceptable color difference. For most industrial applications of color-difference equations, the question of how to define an acceptable color difference has received considerably more attention than the determination of perceivable color difference levels. In the past, researchers determined the acceptability (as opposed to perceptibility) of color difference between two samples through subjective rating procedures. These acceptability ratings were then compared to calculated values of color difference. Keuhni (1970) and Jaeckel (1973) both made significant contributions to understanding the correlation between values determined by color-difference formulae and consumer acceptability in the textile industry. Keuhni stated that it was doubtful a globally ideal color-difference formula is possible for two reasons. First, an ideal formula must be capable of determining what perceivable and acceptable color differences are, and second, such a formula must do so throughout an entire color space. Keuhni believed the problem of defining acceptable color difference far more complex than that of defining perceivable color difference. Acceptability, he stated, must be concerned with the physiological differences existing amongst consumers, the economics of the market, trends in preference for certain colored products, and even the consumer's emotional state.

Keuhni reported that results of other research (Davidson and Friede, 1953; Thurner and Walther, 1969) confirmed the best correlation between perceivable color differences in textiles was obtained using a formula based

on MacAdam (1942, 1943) ellipses, despite the fact that MacAdam's work used emissive stimuli in a perceived color-difference paradigm. However, Keuhni points out that a satisfactory formula does not exist for describing acceptable color differences in textiles, and that perceived color-difference formulae were of little significance in addressing the issue.

Jaeckel (1973) obtained moderately successful correlations between acceptable differences in textiles and values obtained from 20 color-difference equations. Particularly strong correlations were found between acceptability scores and color-difference formulae based on Adam's Chromatic Value (i.e., Glasser Cube Root Formula). The work of Adams (1942) was based upon the postulation that color-difference mechanisms producing chromatic sensation are R and G cones to provide the red/green response and B and G cones to provide the yellow/blue response.

Psychophysical methods for color difference assessment. Sugiyama and Wright (1963) employed the method of paired comparisons to investigate perceived color difference between chips made from Munsell papers. Pairs of chips were of the same hue and luminous reflectance, but differed in chroma. Stimuli were viewed simultaneously without distance separation, and subtended approximately five degrees of visual angle. In judging the color differences between pairs, subjects were instructed to assign positive and negative integers to indicated the magnitude of color difference. Results were analyzed using a number of statistical methods common in psychophysical evaluations, including the Scheffe and Thurstone-Mosteller techniques.

Sugiyama and Wright concluded that all methods used in examining the data gave approximately the same results, although the authors note that some statistical methods were easier to employ than others. Their findings suggested a nonlinear relationship between paired comparison judgements and the statements of statistical methods utilized when rating scales were coarse. Sugiyama and Wright further concluded that the method of paired comparison for color-difference assessments requires a scale of minimal resolution to be defined experimentally, but that the subject, in a practice trial, should have the freedom of choosing the end points of this scale. In doing so, Sugiyama and Wright reported that a linear relationship would be maintained between the judged differences and statistical estimates of the methods investigated.

In 1964, Sugiyama and Wright used the same experimental situation to investigate the method of ratio comparisons for color-difference assessment. The authors stated that when an absolute value of difference is required, the ratio comparison method should be applied. However, if relative differences will suffice, then the paired comparison method was effective. Furthermore, while the method of ratio comparisons may provide a more quantitative assessment of color differences, it also places significantly greater demands on the subject.

Sugiyama and Wright (1964) believed that if the attributes of stimuli could be addressed in a qualitative fashion, then results from ratio and paired comparisons would be related linearly. Therefore, in situations such as the investigation of perceived variation in saturation, scale values obtained through either method would be closely related. This assertion, in fact,

proved to be true. Sugiyama and Wright reported that both methods of judgement resulted in reliable assessments of color difference.

Wright (1965) investigated perceived color differences by employing the method of multidimensional ratio-scaling. The author used the same color tiles utilized in the two Sugiyama and Wright (1963, 1964) studies. While Wright was not the first to employ the multidimensional scaling methodology in color difference assessment, he was the first to claim that:

> "... the analysis indicated that all colors could be represented by points in a two-dimensional Euclidean space in which distances between two points were proportional to observed color differences independent of the location of the points."

Helm (1964) had reported that a multidimensional ratio scaling analysis technique resulted in a logarithmic relationship from a successive interval experiment. Helm claimed that the particular method he had utilized was an appropriate technique for scaling color differences. Thus, no concensus developed regarding the optimal psychophysical method of assessment.

Moderate and large reflective color differences. Coates, Provost, and Rigg (1970), Coates, Day, Provost, and Rigg (1972), and Coates, Provost, and, Rigg (1972) conducted a series of experiments for the Color Measurement Committee of the Society of Dyers and Colourists. The primary goal of these studies was to examine the relationships between color-difference measurements and results obtained under various conditions and methods of assessment. The first study reported by Coates et al. (1970) used glossy paint samples which varied in size and method of display. Large color differences existed between the samples and their standard (10 - 25 ΔE CIE 1964), and

subjects rank ordered the samples according to the magnitude of perceived color difference. Only one standard and set of samples (green in color) was examined in this study.

Unfortunately, the methodology Coates et al. (1970) employed varied with the characteristics of the stimuli under examination. When samples subtended two degrees, subjects viewed all of the samples as arranged in a circle around the standard and separated by two degrees. Larger sized samples were allowed to be moved about freely during the assessment process, and no gap existed when large samples were examined. Correlations were then determined for the rank ordering of samples with respect to calculated color differences. Furthermore, the 1964 CIE supplementary standard observer equation used by Coates et al. is intended for stimuli which subtend 10 degrees or more of visual angle. Yet, the majority of the stimuli used by Coates et al. were 2 degrees in size.

Coates et al. concluded in this first experiment that the degree of observed correlation between the standard and its samples were influenced by the size of the stimulus, the magnitude of the color difference, and the conditions under which they were presented. In comparison with a similar study, Coates et al. reported that equations which were highly correlated with similar stimuli of small color difference were not highly correlated when large color differences existed. The authors cited previous research to support the observed effects of stimulus size on the color assessment process (Coates, Day, and Rigg, 1969). Coates et al. (1970) concluded, "It follows that tests of equations are relevant only when appropriate viewing conditions are used"

referring to the conditions under which the data were collected for the establishment of the formulae examined.

In the second study reported by Coates et al. (1972) a series of acceptability data (collected by another researcher) was transformed into a visual color-difference scale. Again, the authors reported that the data do not correlate well with calculated values from various color-difference formulae. Coates et al. reiterated that the assessment of color differences was dependent upon the conditions under which the assessments were conducted, and that different equations were required for different conditions.

In the third and final study, Coates et al. (1972) examined correlations between the results obtained through various experimental methodologies. The study reported results obtained through ratio, rank order, and paired comparison scaling. The goal was to compare methodologies with respect to their convenience and reliability. Again, a limited set of glossy green painted samples, similar to those used previously, were assessed for color differences. The authors theorized that if scaled values were directly proportional to the actual differences, then the obtained values from one method should correlate with those of other methods. This assumption, in fact, proved to be true for at least a limited number of stimuli examined.

Coates et al. (1972) appear to be the first researchers to specifically question the effect of subject experience on color difference assessment. The authors thought it reasonable to assume that experienced subjects would possess internalized criteria on which to base their assessments. Novices, on the other hand, would not have developed criteria based upon experience and would base their assessments on perceived differences. In an acceptability

task, novice subjects would be expected to assign a level of acceptability to a perceived difference without the benefit of established criteria. Coates et al. hypothesized that this difference in experience might result in differences for the orientation of color attributes between novices and experts if the results were to be plotted in an elliptical form. However, there is no known published work by the authors which specifically tests this hypothesis.

Two studies by Mattiello and Guirao (1974a, 1974b) asked subjects to scale reflective color surfaces using the method of magnitude estimation. One study examined perceived saturation for two sets of samples subtending 4.0 and 0.7 degrees. A second study examined the estimation of reflective lightness using 4.0-degree stimuli. Both studies were conducted under lighting conditions which simulated D65. The authors concluded, like others before them, that saturation could be considered a sensory dimension which obeys the psychophysical power law.

Several years later Lozano (1977, 1980) used the very same data obtained by Mattiello and Guirao to evaluate 11 color-difference formulae. The initial part of Lozano's (1977) work dealt with the evaluation of color-difference equations for differences in lightness, while hue and saturation were held constant (the first of two studies by Mattiello and Guirao). Lozano's second study evaluated saturation while hue and lightness were held nearly constant. The magnitude of color differences used in these studies is large in comparison to threshold differences. Specifically, the samples compared in the studies by Mattiello and Guirao ranged from 15 +/- 10 to 18 +/- 2 ΔE CIELAB units.

Lozano compared the calculated color-difference values from 11 different formulae with each of the magnitude estimations for sample pairs collected by Mattiello and Guirao. Correlation coefficients were determined from these comparisons. For both studies, Lozano found CIELAB to be consistently correlated with reported magnitude estimations. Additional formulae were also highly correlated, but these particular formulae (the Richter and Adams-Nickerson formulae) were closely related to CIELAB and expected to perform in a similar fashion.

While Lozano made a significant attempt at evaluating numerous color-difference formulae, several concerns associated with these studies exist. First, the enormous variability in color differences existing between stimuli meant that data did not lend themselves to an accurate characterization of a uniform color space. Much of the variability of the color differences was closely correlated to various spectral regions, with variability being significantly greater in some regions than others. In addition, the use of various stimulus sizes, and in some cases different viewing conditions, raises the question as to whether the same analyses should not be performed on data collected under more uniform conditions.

Morely, Munn, and Billmeyer (1975) were concerned with the application of color-difference formulae in industrial assessments. The authors state two important points which should not be compromised in this area: first, that color differences be examined which are considerably larger than threshold; and second, given the fact that the definition of acceptable color difference varies as a function of the application, visual judgements should not be based on acceptability criteria.

Morely et al. (1975) employed categorical scaling of color differences for coated tinplate samples subtending two degrees. With minimal separation between stimuli, subjects based assessments on a six-point scale ranging from "No Difference" to "Very Large Difference." Subjects examined 19 color samples, distributed throughout color space, and 30 variations which surrounded each of these 19. However, the 30 variations were not systematically located about the samples. Instead, the variations formed a "cloud reasonably distributed" around the samples, and the procedures used were less than ideal.

A total of 20 subjects viewed each combination of the sample and its variations. However, the same subjects did not assess all 19 color samples. Furthermore, data collection took place much like the stimuli were generated, "over a period of years" with subjects who appeared to have been experienced (possibly to be considered experts) in color discrimination.

Morely et al. (1975) transformed the ordinal data into an interval scale and regressed 11 calculated color-difference measures with these results. The outcome indicated that no one color difference formula provided a high correlation with results from all regions of color space. They did, however, report three formulae which consistently performed relatively well for all regions. The 1976 CIELAB, ANLAB 40, and Saunderson-Milner formulae never resulted in a correlation coefficient of less than $r = 0.70$ for all the samples examined. From a statistical standpoint, these three formulae were not any better than five other formulae when data for all samples were combined. Further analysis showed that both color examined and formulae were significant factors at the 0.01 level of confidence.

Training and the Assessment of Color Differences

Very little is known regarding the effects of experience on color-difference assessment. It is possible to imagine that considerable experience with one particular formula might result in an individual's judgements mimicking differences as defined by that formula. While a trained judge is not physically more capable of perceiving color differences, experience may establish task dependent criteria for making color-difference judgements.

Indow and Matsushima (1974) conducted three experiments designed to examine differences in color assessment between naive and trained subjects. In the first experiment, subjects viewed 24 colored paper samples which varied along all dimensions. Stimuli varied in order of magnitude of color difference around one pale-green standard. Subjects were asked to rank order samples relative to a standard on the basis of similarity. Subjects were not provided with a modulus on which to base this ordering. Indow and Matsushima defined subjects to be trained in color assessment by providing them the correct order upon the completion of each trial for a series of 60 trials. Likewise, the untrained subjects were not provided with feedback. All subjects were university students with no previous experience in judging color differences. In analyzing the data, the authors expected to observe a convergence of reported values towards the calculated values for the trained subjects. However, only limited convergence towards the calculated values was expected for the novice subjects. In fact, little or no convergence was observed for either group. The authors concluded that training had no effect on the ability to judge color differences.

In a second experiment, Indow and Matsushima employed essentially the same conditions, using the same subjects from the first experiment. The objective in this experiment was to examine larger color differences. Again, no systematic change towards convergence with the calculated values was observed.

In the third and final experiment, Indow and Matsushima provided subjects with a modulus on which to base their scaling. This modulus was not present in the first two experiments. In addition, the authors significantly increased the number of trials in which subjects participated from 60 to 700. Once again no convergence towards the calculated color-difference values was found for either of the two groups. Only a marginal convergence was observed for both groups over the first 100 of 700 trials.

In their concluding remarks, Indow and Matsushima (1974) stated that "intensive" training in color-difference assessment towards a specific color-difference formula is not effective. However, the authors admitted not knowing what effect experience in an industrial setting would produce when training occurred over a period of years. Based upon their experiences in these experiments, the authors felt that in making color-difference assessments an overall impression of the total color difference was of greatest importance. Only in obvious cases did they believe that subjects, trained or untrained, could tell in what dimension two colors differed.

Indow and Watanabe (1980) examined the effects of training on the discrimination of systematic shifts in all three psychophysically correlated dimensions of color space. Through training in the identification of colors in Munsell notation, the authors hoped to address the following three questions.

First, what was the effect of training? Second, what level of accuracy can be obtained? Third, in what directions was absolute identification most likely to deviate from the correct notation? Strictly speaking, this work was not an experiment in assessing color differences. However, it does provide insight regarding the assessment of color variation along attribute-related dimensions.

Under controlled lighting conditions, subjects viewed large colored chips representing a renotated version of the Munsell system. Stimuli consisted of 520 chips representing 40 different hues. Variations in value and chroma were also incorporated. Step sizes for hue, value, and chroma were 2.5 H, 0.5 V, and 1.0 C respectively. Chips were presented one at a time with subjects estimating the three attribute values for each chip by the step sizes listed above. Immediately after each estimation the subject was informed of the correct Munsell notation values for that chip. Subjects viewed each chip twice.

Indow and Watanabe reported that the majority of learning to scale Munsell chips took place prior to having seen all chips at least once. They believed this was the result of the subject's ability to establish an "effective global scheme" in evaluating the attributes of hue, value, and chroma. However, subjects' ability to perform the estimates was not equally effective for all three attributes. The authors reported that subject schemes appeared to be easily transferred between various samples for the attributes of value and chroma, but not for hue. It was theorized that some conflict might exist for subjects accustomed to identifying hue by various color names versus the experimental condition. The authors suggested that similar conflicts did not

appear to exist for identifying attributes of value and chroma, possibly because they are normally thought of in a conceptually less discrete fashion. Further evaluation showed saturated colors to be judged lighter for dark values, while low levels of saturation were overestimated. Similar to previous work, the authors reported that training effects appeared during initial exposure and quickly leveled off with the duration of the experiment.

Unfortunately, the work performed by Indow and Matsushima (1974) and Indow and Watanabe (1980) did not attempt to examine the responses of highly trained judges. The work of these authors appears, therefore, to be of limited application in addressing the true effects of training and color-difference judgement.

Color-Difference Evaluation in Color Prints

Unpublished work performed by Wood, Jacobsen, Attridge, and Pointer (1988) investigated the minimally perceivable color differences for color photographic prints. The aim of this study was to determine ellipses which represented minimally perceivable color differences in 1976 CIELAB color space and their relation to three standard color difference measures: MacAdam ellipses, CMC(l:c) ellipses, and CIELAB unit ellipses. The CMC(l:c) formula was developed by Clarke, McDonald, and Rigg (1984) and has been considered by the Society of Dyers and Colourists, CIE, and ISO for possible replacement of the 1976 CIELAB UCS.

Wood et al. generated 3042 color prints (8 x 13 cm) on Kodak Ektacolor 78F paper. Each stimulus represented 1 of 168 color variations for each of the 18 standard color patches which make up the Macbeth Color Checker Chart.

Lightness variation within a set was maintained fairly constant, though lightness varied among the 18 sets. Generation of these stimuli was aided through the use of electronic imaging techniques. All prints were compared side-by-side as subjects reported, in a forced choice fashion, whether a perceivable difference between a stimulus patch and a standard existed. All comparisons were made under controlled lighting conditions simulating daylight viewing.

Analysis of the results was conducted by plotting the coordinates in a* by b* color space of those stimulus patches which no subjects reported as matching the standard. Ellipses were therefore determined to represent the boundaries of minimally perceivable differences for each standard color patch for the particular lightness (L*) values examined. Again, only one lightness level per standard patch was examined. Some fitting of the data, as determined by various methods, was conducted and the lengths of the a* and b* axes were determined. These ellipses were then compared statistically for size, shape, and angle of inclination with similar experimental ellipses of the same color centers for CIELAB, CMC(1:1), and the MacAdam ellipses.

Wood et al. concluded that ellipses determined by the CMC (l:c) color difference measure fit the obtained experimental data more closely than did the CIELAB unit ellipses or MacAdam ellipses. The authors went on to suggest that tolerances for small color differences in photographic prints could be predicted using the CMC(1:1) difference equations for the conditions represented. However, no recommendations were made regarding the perception of large color differences.

RESEARCH NEEDS

As described in the preceding review of the literature, previous work has failed to provide structured information concerning the perception of large color differences. What general information is available in the existing literature suggests that results are very specific to the viewing conditions and type of stimuli employed. Therefore, research is required which addresses the specific concerns and conditions surrounding the perception of moderate and large color differences in photographic prints. The remainder of this thesis discusses a study in which a magnitude estimate procedure was employed. Subjects in this study judged the total color difference existing between stimulus patches made of color photographic paper. These patches differed by moderate and large amounts (5 ΔE and 10 ΔE CIELAB, respectively). Five color-difference formulae were then evaluated for their ability to represent the obtained magnitude estimation results. Furthermore, two populations of subjects, novices and experts, participated in order to examine the effects of training on the perception of moderate and large color-differences in photographic prints.

METHOD

Subjects

A total of 20 subjects ranging in age from 18 to 45 took part in the study. Ten subjects had no practical experience in assessing color differences and limited, if any, knowledge of the representation of color in three-dimensional space. These subjects (five males and five females) were classified as novices (mean age = 22.5). Novice subjects were students at Virginia Polytechnic Institute and State University and were reimbursed in the amount of $5 per hour. An additional $5 bonus was awarded to subjects who arrived on schedule for their appointments. All experimental sessions for novice subjects were performed in the Displays and Controls Laboratory, Department of Industrial and Systems Engineering.

The remaining 10 subjects, classified as experts, each possessed a minimum of three years experience in assessing color differences in the photographic industry. Experts also had a working familiarity with the three-dimensional representation of perceptual color attributes (lightness, hue, and chroma). The mean years experience of expert subjects was 7.4, and their mean age was 34.0. All expert subjects (six males and four females) were employees of the Eastman Kodak Company, and participation was in conjunction with their regular duties at Kodak. Expert subjects were therefore not financially reimbursed for their participation. All sessions in which expert subjects participated were conducted at the Eastman Kodak Research Laboratories, Building 59.

All subjects were tested for near and far (20/25) visual acuity, corrected or non-corrected, using a Bausch and Lomb Orthorater or an Optec 2000 vision tester. Two vision testers were required to eliminate the need of transporting either of the vision testers to an alternate site. Subjects' ability to perceive and distinguish color differences was examined using the Farnsworth-Munsell 100-Hue Test for color vision. A total error score no greater than 16 was permitted by either novice or expert subjects to qualify for participation in this study. Subjects performed the 100-Hue Test only once under lighting conditions identical to those used throughout the remainder of the experiment. These lighting conditions were not those specified in the Farnsworth-Munsell 100-Hue Test manual (Farnsworth, 1957). It is, therefore, uncertain exactly how the criterion established for this study relates to other Farnsworth-Munsell 100-Hue Test results under recommended conditions of viewing.

Apparatus

Viewing conditions. The assessment of color differences was conducted under controlled lighting conditions using a Macbeth portable viewing booth (Kollmorgen Corporation) with florescent lamps simulating a diffuse D5000 illuminant. The chromaticity coordinates of the illuminant were $x = 0.325$ and $y = 0.382$ in approximately 1000 lux. All assessments were conducted using a diffuse/45-degree viewing geometry at a fixed viewing distance of 356 mm. This viewing distance was based upon the work of Zwick (1984).

The diffuse illuminant was located directly over the stimulus, while the angle of incidence of the subject's line of sight was 45 degrees from the

stimulus surface. This viewing geometry was maintained for all subjects through the use of an adjustable-height chair and a fixed-position headrest. Subjects were required to place their foreheads against the padded headrest at all times while making color-difference assessments.

The viewing booth was lined with a matte-surfaced neutral-color paper to reduce the occurence of chromatic induction in the color-difference judgment process. The "Thunder Grey" paper, manufactured by the BD Company of Erie PA, had chromaticity coordinates under the above illuminant conditions of $x = 0.329$ and $y = 0.333$. Subjects were also required to wear a neutral-colored laboratory coat while making assessments. The laboratory coat prevented reflections from subject's clothing from altering the viewing conditions. Subjects wore white cotton gloves at all times to prevent soiling the stimuli and other apparatus used in the study. A color photocopy of the viewing booth and other supporting apparatus is shown in Figure 1.

Stimuli. Stimuli consisted of 328 round patches generated from color photographic print paper (Kodak Ektacolor Plus, F Surface); each patch was 12.7 mm in diameter. These patches subtended 2.0 degrees of visual angle when viewed at a distance of 356 mm. Sets of 40 comparison stimuli were created for each of eight color regions to be examined. This resulted in 320 stimuli which varied about eight color standard stimuli (328 total stimulus patches). The color standards associated with the eight color regions are listed in Table 1 and plotted in Figure 2.

Figure 1. Viewing booth and supporting apparatus.

Table 1. Chromaticity Coordinates and CIELAB Values for the Standard Stimuli of the Eight Color Regions.

Color Region	x	y	Y	a*	b*	L*	C*
Magenta	.36	.28	22.02	28.50	-14.78	53.78	32.10
Green	.34	.44	21.51	-21.94	22.60	53.06	31.50
Red	.42	.34	21.12	25.06	7.41	52.70	26.13
Blue	.28	.31	21.70	-3.68	-17.36	53.71	17.75
Yellow	.47	.43	21.45	11.96	43.21	53.28	44.83
Neutral	.34	.36	23.64	0.89	2.65	54.88	2.80
Cyan	.26	.34	21.54	-21.41	-11.12	53.12	24.12
Caucasian	.41	.37	37.97	17.38	18.26	68.50	25.21

With the exception of the color standard for the Caucasian skin region, all additional standard stimuli were approximately located in the CIE L* = 53 plane. The chroma value (the a*, b* dimensions) for each of the eight color regions was determined in part by the achievable gamut of the photographic paper.

The 40 comparison stimuli deviated from the standard stimuli in a systematic fashion, with 20 stimuli differing by 5 ΔE CIELAB units and 20 by 10 ΔE CIELAB units. These sets formed two spheres around each of the eight standards, the radii of which were 5 +/- 2 or 10 +/- 2 ΔE CIELAB units (Figure 3). The comparison stimuli for both levels of color difference, 5 and 10 ΔE, included 14 direction specific variations from the standard stimulus and six replicate patches. The six replicate stimuli examined the independent axial differences of +/- a*, +/- b* and +/- L* (Table 2). The exact locations of the stimuli in CIELAB color space are provided in Appendix A (Tables A-1 though A-8).

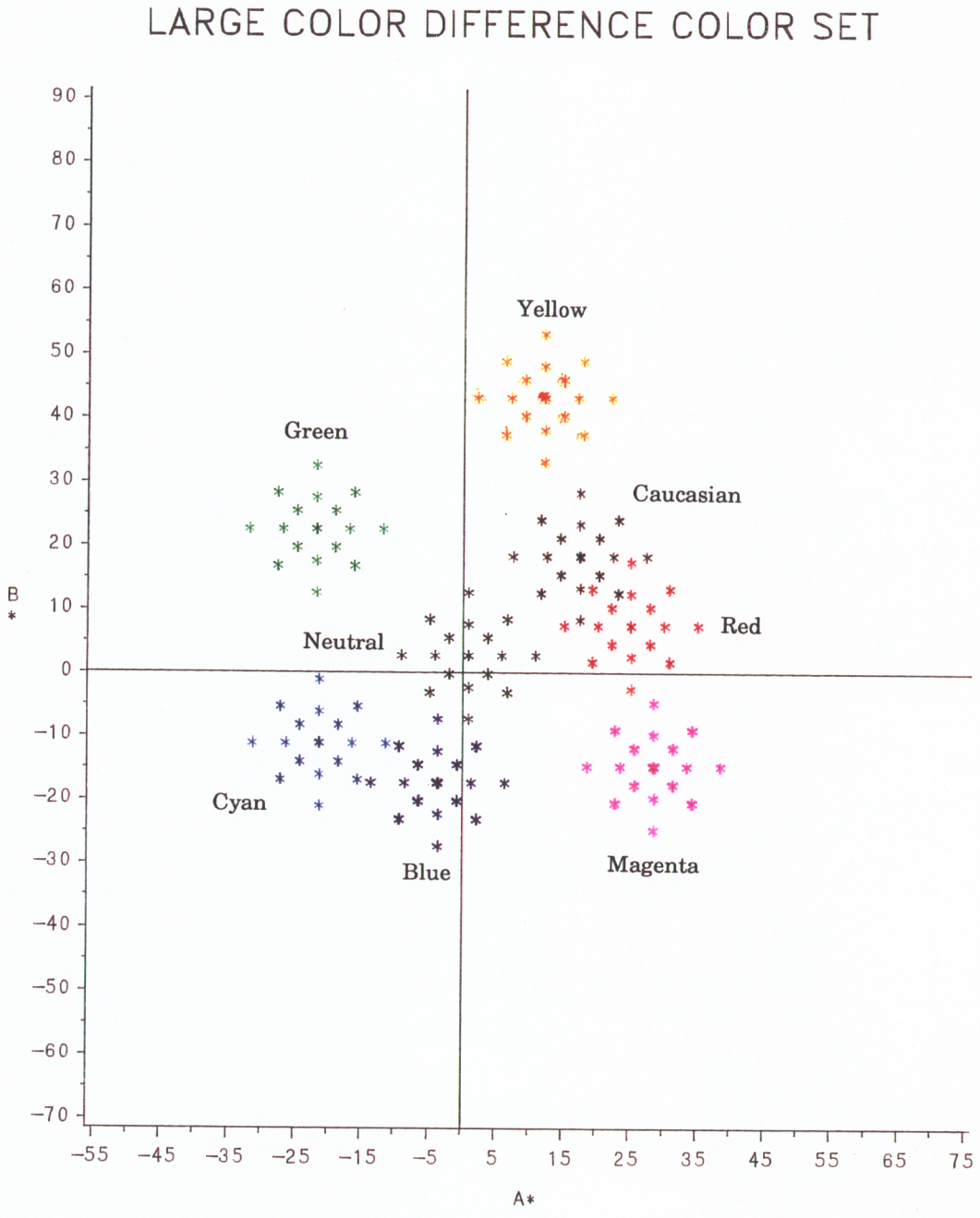
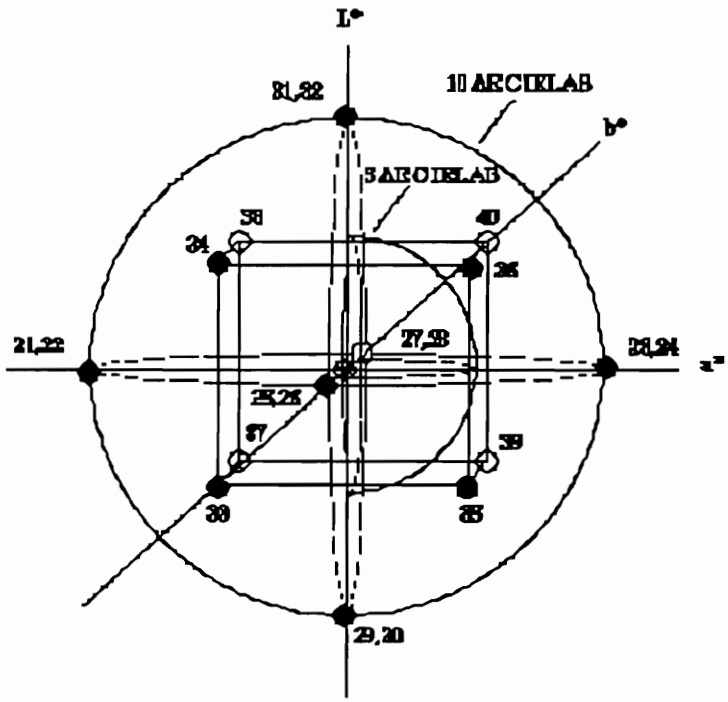


Figure 2. Idealized location of stimuli in CIELAB color space.



Comparison stimuli of 10 ΔE CIELAB units are labeled 21 to 40, the standard stimulus is centrally located. Stimuli 1 to 20 are similarly located at 5 ΔE CIELAB units. The radial distance is an a*, b*, L* combination, while the axial distances are independent changes of a*, b*, and L*.

Figure 3. Location of the comparison stimuli in three-dimensional space.

Table 2. Variations in Direction, Size, and Dimension of Comparison Stimuli (1 though 40) for the Standard Stimuli of All Color Regions.

	Axis			
Direction/Size	a*	b*	L*	Combinations of a*, b*, L*
- 5 ΔE	1,2	5,6	9,10	13, 14, 15, 16, 17, 18, 19, 20
+ 5 ΔE	3,4	7,8	11,12	
- 10 ΔE	21,22	25,26	29,30	33, 34, 35, 36, 37, 38, 39, 40
+ 10 ΔE	23,24	27,28	31,32	

Examples of the stimuli are shown in Figure 4, and a specific example of the range of color differences from the standard is presented in Figure 5. The color rendition of Figures 4 and 5 are approximations for purposes of example only (this is the result of limitations in the color photocopying process).

Supporting apparatus. Some additional materials specific to the task subjects performed were employed in conducting this experiment. For the sake of clarity, this apparatus is discussed in the Procedures section of this document.

Experimental Design

Independent variables. A mixed-factor factorial design was employed. The between-subjects portion of this design examined differences between populations of subjects with differing levels of experience (i.e., novice versus expert subjects with subjects nested in experience). The within-subjects

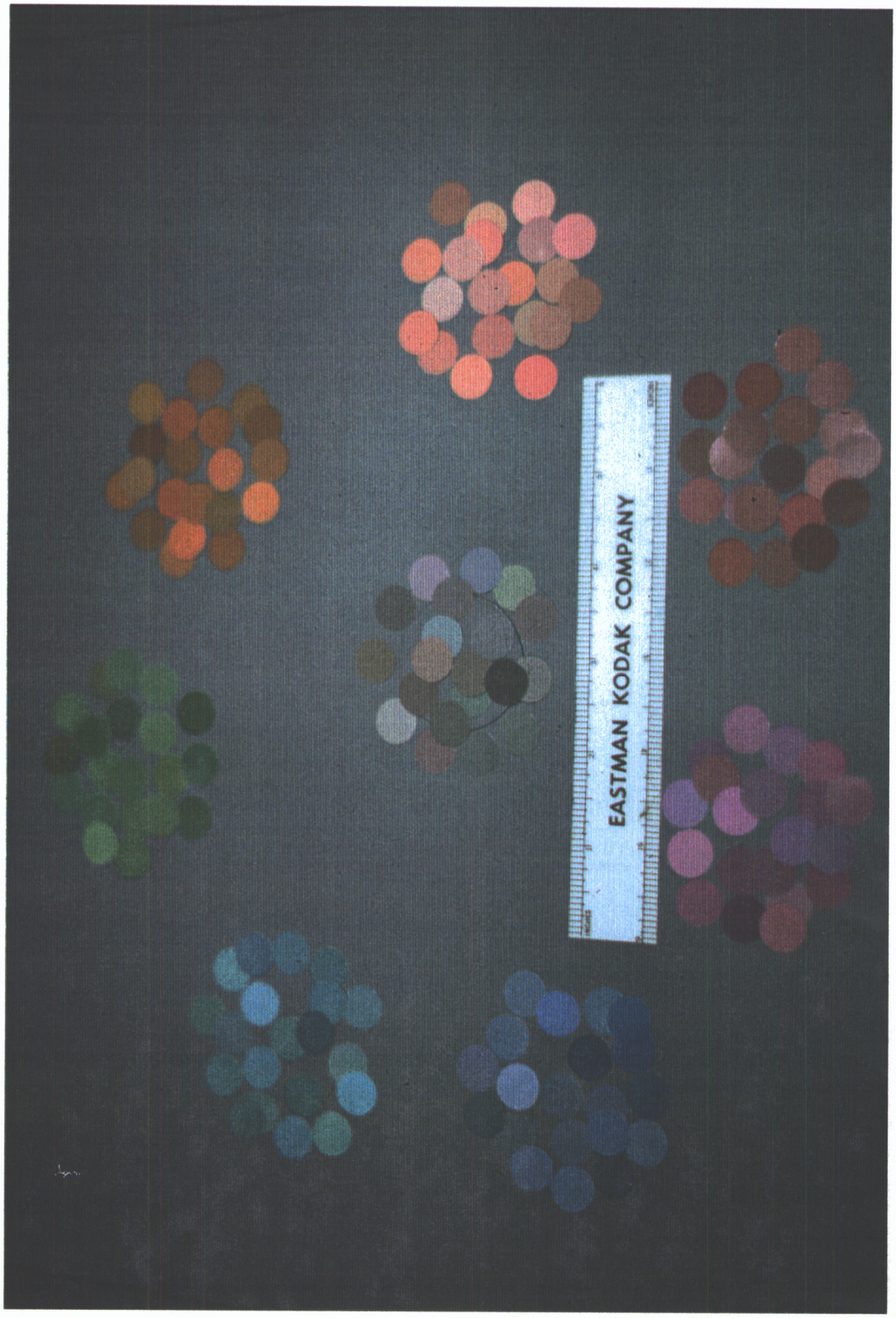


Figure 4. Examples of the color stimuli employed in the study.

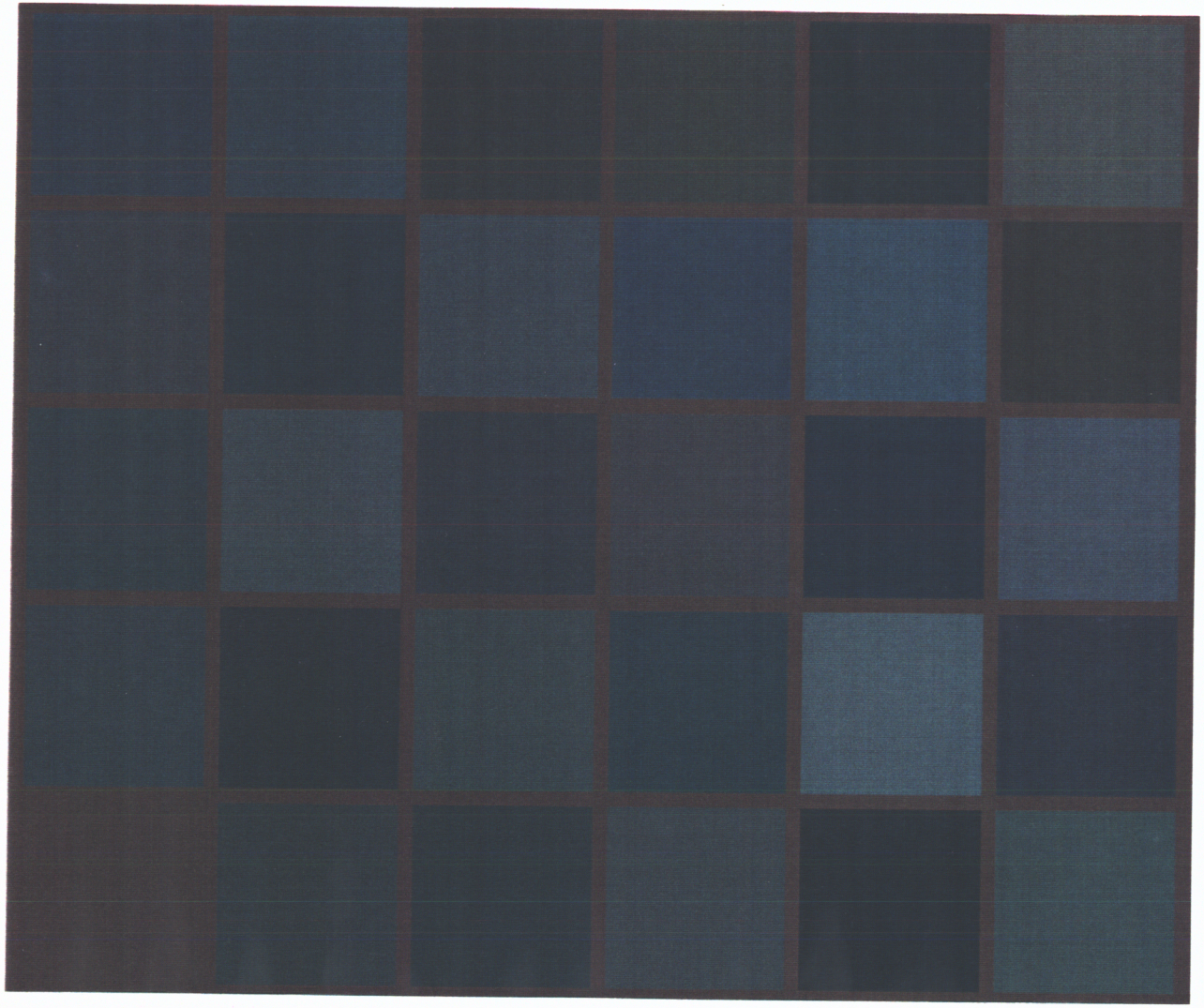


Figure 5. An example of the range of color differences which existed among stimuli for the cyan color region.

portion examined effects of the eight different color regions, levels of color difference (5 and 10 ΔE CIELAB), and variations in comparison stimuli (nested in both color region and level of difference). All subjects examined each of the comparison stimuli relative to their standards twice. This resulted in two replications per subject for each cell in the 20 x 2 x 8 x 2 mixed-factor experimental design. A graphic illustration of the experimental design is shown in Figure 6.

Dependent Variable. Color differences between the standard stimuli and the comparison stimuli were assessed using the method of magnitude estimation (Stevens, 1975). Subjects provided subjective values regarding the overall magnitude of the color differences they perceived to exist between a standard and comparison stimulus. The method of magnitude estimation allowed for the quantitative comparison of color-difference formulae and the collection of large amounts of data in a timely fashion. Given the large number of stimuli involved, the time required to collect the data was an important factor in the design of this experiment. Various researchers have been successful in employing the method of magnitude estimation in similar studies (Indow and Stevens, 1966; Lozano, 1977, 1980; Mattiello and Guirao, 1974a, 1974b).

Procedure

The experiment required several sessions for each subject. The first session was dedicated to screening for the visual acuity and color discrimination requirements described previously. All potential subjects provided informed

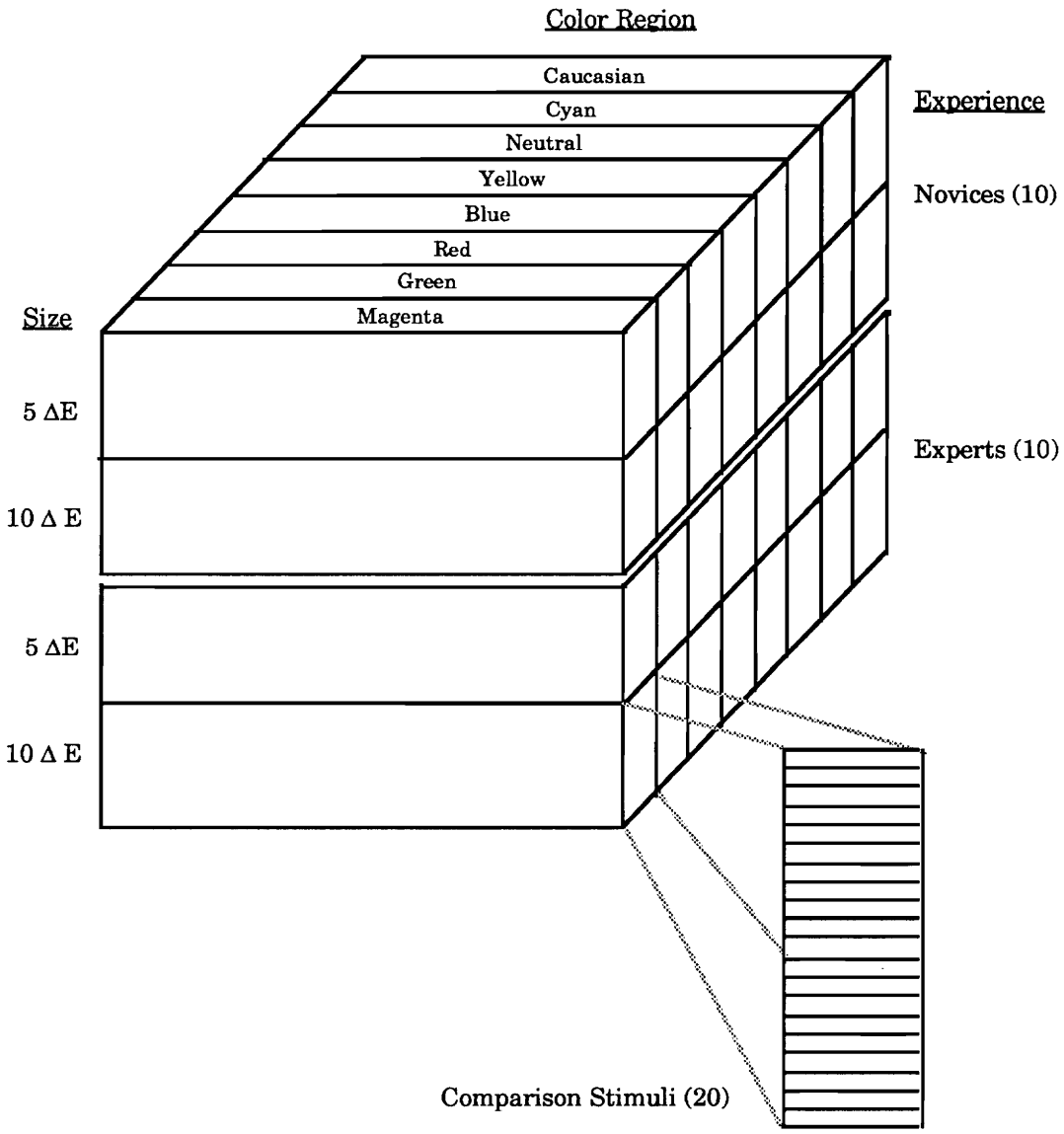


Figure 6. Experimental design.

consent prior to the screening procedure (Appendix B). Individuals who did not meet the requirements of the experiment were paid for participating in the screening process and released from the study. Individuals who did meet the requirements received a brief description of the experiment and were invited to participate. Additional sessions were then scheduled for purposes of instruction and data collection.

In the second session, subjects were reminded of the purpose of the study and provided with an extensive set of instructions prior to beginning the experiment. Due to the length and complexity of the written instructions (Appendix C), additional instruction was provided to subjects using a videotaped "walk-through" of the written material. Subjects were prompted in the written instructions to watch specific segments of the videotape which coincided with the written material they had just read. In general, the videotaped segments showed the actions which were described in the written instructions. The videotaped instruction was included to insure that subjects fully understood the procedures they were asked to perform in the experiment.

Following a brief example of the method of magnitude estimation, subjects were allowed to view a sample set of stimuli. These stimuli were not included in data collection, but were shown to subjects to provide then with the opportunity to practice manipulating the stimuli in accordance with the instructions. In conducting the color-difference assessments, standard stimuli were mounted to a 20% reflectance neutral board on a raised surface 1.0 mm in height. The raised surface on which the standard stimulus was mounted maintained a visual angle separation of two degrees between it and

the comparison stimulus (Figure 7). Comparison stimuli were freely manipulated by subjects while making comparisons with the standard stimulus. Only one assessment at a time was allowed. Therefore, only one comparison stimulus was placed near the standard while color-difference judgements took place. All other comparison stimuli were placed 190.5 mm (30 degrees) to the right of the standard.

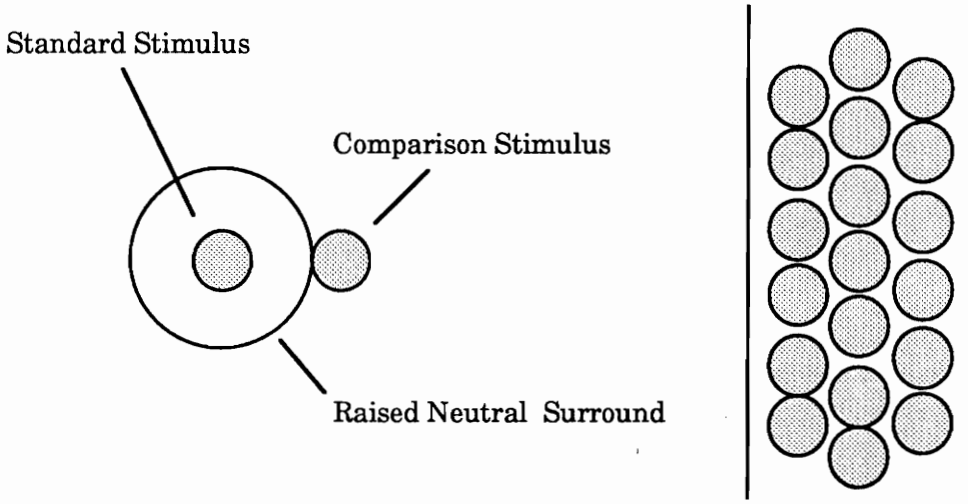


Figure 7. Method of displaying stimuli.

To facilitate the assignment of magnitude estimates, the first task subjects were required to perform prior to data collection was the establishment of a modulus set. The modulus set allowed for the comparison of perceived color differences across all eight color regions examined. This task was performed independently by each subject. The stimuli consisted of seven neutral stimuli ranging from L* 35 to 60 in incremental steps of 5 L* units. The L* 60 stimulus was defined as the standard for comparison in the modulus set.

Individual subjects assigned magnitude estimates to the perceived color differences they detected between the modulus standard and each of the additional six modulus stimuli. This set of stimuli, with its subject-dependent color difference magnitude estimates, was used by subjects as a modulus for all further color-difference assessments. The actual magnitude estimate values provided by subjects were written in black onto small pieces of clear acetate and placed alongside the comparison stimuli for which the values had been reported. The only constraint was that all values assigned must be positive whole numbers.

The above procedure resulted in a modulus set for each subject with measured color differences ranging from 0 to 30 ΔE CIELAB units (Figure 8). This range was found to be appropriate for the perceived color differences represented by the standard and comparison stimuli in the remainder of the experiment. The modulus set and assigned difference values always remained visible to subjects, but separated by 190.5 mm (30 degrees) from other stimulus comparisons. Neutral stimuli were selected for the modulus set on the basis that any biasing of future assessments from the selection of this reference would affect all other stimuli equally.

Subjects were instructed to refer to the modulus set whenever necessary during the experiment. It was felt that the use of a modulus set in assigning magnitude estimates would result in perceptually uniform responses across color regions. However, the ranges of subject assessments were not bound by the range of values used in the modulus set. Though subjects were restricted to using positive whole integers in making magnitude estimates. Once the

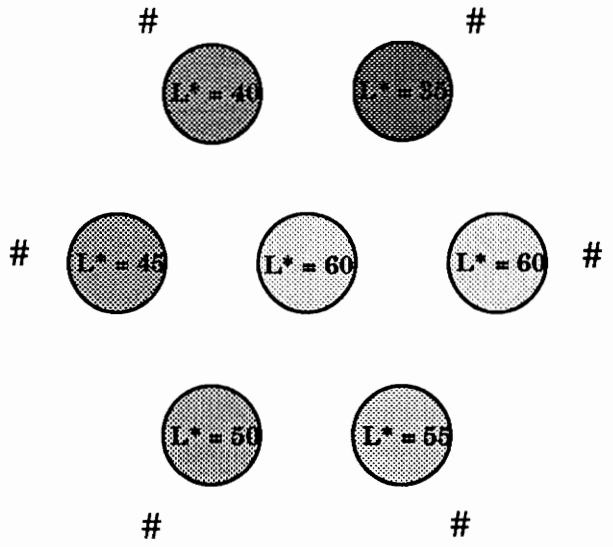


Figure 8. Experimental modulus set.

modulus set was established, subjects completed the experiment instructions and watched a final segment of the videotape.

Final instructions included the use of an ordering board which was provided to keep track of the order in which stimulus comparisons were made. Subjects were instructed to verbally report each value after having made a comparison between two stimuli. They were then instructed to place the comparison stimulus onto the ordering board in the order in which comparisons were made. The ordering board was labeled to accommodate all of the comparison stimuli shown in one trial. This procedure allowed the experimenter to record the reported values at the time of the assessment and to relate those values to the specific comparison stimuli between trials. Figure 9 shows the design of the ordering board.

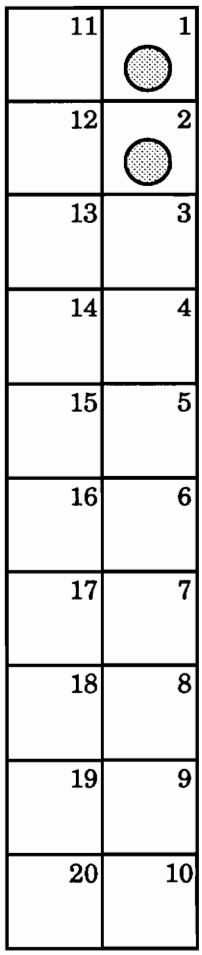


Figure 9. Ordering board.

The back side of all comparison stimuli were coded in order to relate magnitude estimates with comparison stimuli of specific direction and magnitude of deviation from the standard. Once all stimuli in a trial had been assessed, the experimenter, with the aid of a piece of clear plastic, was able to examine the coded values on the backs of the comparison stimuli. Order of placement onto the ordering board permitted the experimenter to pair the comparison stimulus with the reported magnitude estimate of color difference.

Lastly, subjects were reminded to:

1. Wear the cotton gloves and laboratory coat at all times.
2. Maintain their head against the headrest.
3. Compare only one comparison stimulus to the standard at a time.
4. Assign and report numerical values taking the modulus set into consideration.
5. Place comparison patches onto the ordering board in the order which assessments were made.

While 40 comparison stimuli were generated around each of the eight standards, subjects assessed only 20 comparison stimuli at a time (ten - 5 ΔEand ten - 10 ΔE per trial). Stimuli were examined in sets of 20 so that replicate stimuli could be viewed separately. Furthermore, it was felt that 40 stimuli per trial would overwhelm subjects. Subjects were free to choose the order in which comparison stimuli were selected from the set of 20. However, subjects were not allowed to make direct assessments between comparison

stimuli, nor were subjects allowed to order stimuli to facilitate assessments with the standard. The order in which color regions and the associated comparison sets of 20 were viewed was randomly presented.

Once completely assembled, the supporting apparatus appeared as shown in Figure 10. This design was developed based upon the work of several researchers. Specific issues which were of concern included chromatic induction and the effects of distance separation. Chromatic induction is the effect an adjoining stimulus has on the color perception of other stimulus. Jameson and Hurvich (1961) showed the effects of color induction were decreased as the distance separation between two stimuli increased. Oyama and Hsia (1966) arrived at a similar conclusion. A more recent study by Tiplitz-Blackwell and Buchsbaum (1988) reported that the effect of adjoining stimuli decreases exponentially as a function of distance separation.

While most work has been concerned specifically with stimuli which were completely surrounded by an adjoining stimulus, Tiplitz-Blackwell and Buchsbaum theorized that chromatic induction could be observed in virtually any scenario by characterizing this effect as a local phenomenon. Their results suggest that virtually any two fields separated by two degrees of visual arc would be immune to the effects of color induction. Hence, two degrees of separation was included between the standard and comparison stimuli. This separation was maintained by the 1.0 mm raised surface. This design prevented subjects from placing comparison stimuli directly next to, or on top of, the standard stimulus.

Although it appears that two degrees of separation eliminates the effects of chromatic induction, could it also impair the evaluation of the magnitude of

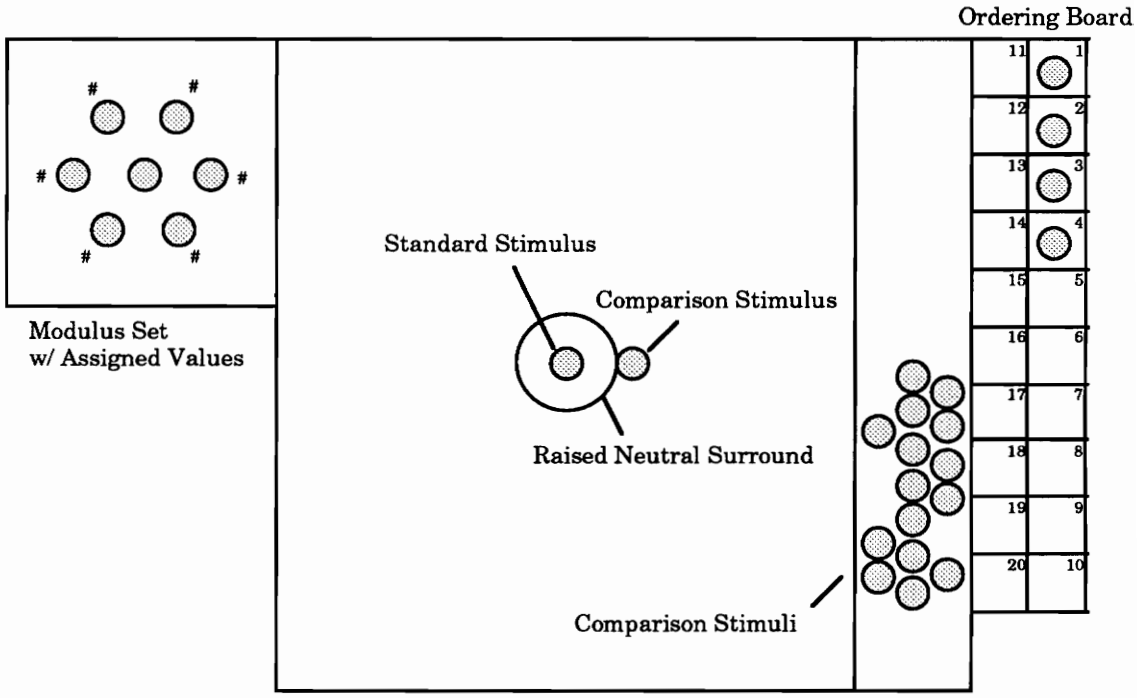


Figure 10. Assemblage of supporting apparatus as viewed by subjects.

color difference? It would seem intuitive that as the distance separation between two stimuli increased, the discriminability of the actual difference between them would decrease. Even the perception of large color differences may have been affected if the distance separation were too great.

Early work by researchers concerned with this issue suggested weighting factors for color difference formulae. Sharpe and Wyszecki (1976) reported that sample separation does impair discrimination of color difference. Specifically, they reported that lightness discrimination was impaired more so than chroma or hue. These findings were even more pronounced when the comparisons were made under poor or impractical observation conditions. Similar results have been presented by Troscianko (1977). However, the work of Sharpe and Wyszecki examined only two levels of distance separation, 0 and approximately 6.5 degrees. These authors suggested that further experimentation with various sizes of angular separation was required. They also believed that under good observation conditions, distance separation would not affect color difference evaluations of large color differences if this distance were reasonable. Good observation conditions were defined as sufficient stimulus size, appropriate illumination, and a light-grey colored separation field, particularly if separation field sizes are smaller than the 6.5 degrees examined by Sharpe and Wyszecki.

The idealized observation conditions recommended by Sharpe and Wyszecki were met in the design of the apparatus and stimulus viewing conditions for this study. It was therefore felt , based upon the reported work of Tiplitz-Blackwell and Buchsbaum (1988), that no dramatic effects of the two-degree separation would affect the magnitude estimates provided by subjects.

Data Reduction

Data normalization. The magnitude estimation procedure employed in this study produced modulus set values which varied significantly across subjects. As a result, all subsequently obtained observations were normalized using a method described by Lane, Catania, and Stevens (1961). This normalization procedure allowed for the removal of variance in the data which was associated with individual modulus set selection. To eliminate intra-observer variability, further steps were performed. The process which incorporates both of these procedures was reported by Engen (1971).

The normalization procedure results in a logarithmic transformation of the magnitude estimate data and determined subject means of replicated observations for each of the 320 comparisons. Mean values were then subtracted from the group means and the differences added back to the individual subject observations. This procedure minimized the sum of squares deviation and forced subject means equal to respective group means.

Subject populations. The normalization procedure was performed separately for the two populations of subjects in order to retain the substantially higher mean values provided by experts. Larger mean responses and the use of a larger range of values to describe color differences might suggest a greater sense of confidence on the part of expert subjects in making color difference judgements. Specifically, expert subjects expressed greater confidence in discriminating perceptually small color differences. As

a result, some expert subjects appeared to have used larger ranges of values in order to allow for a finer level of resolution.

Color regions. The normalization procedure outlined by Engen (1971) was also performed in two separate approaches to account for possible variation associated with the color region. Because the stimuli were generated and specified using CIELAB color space, which is believed to be perceptually non-uniform, magnitude estimate values from the experiment were normalized using two separate approaches. The first approach assumed that variation in the magnitude estimate values was not affected by the eight different color regions stimuli represented. This approach was referred to as the Global approach to data analysis, as data from all color regions were normalized collectively.

The second approach to data normalization to account for effects of color region was referred to as the Local approach. The Local approach assumed that variation in the obtained magnitude estimates was, in part, a result of perceptual non-uniformity among color regions. Therefore, magnitude estimate values were normalized separately for each of the eight color regions. While the relative sizes of the differences between the comparison and standard stimuli were constant for all color regions (levels of 5 and 10 ΔE CIELAB), the apparent perceptually non-uniform nature of the color space meant the various color regions could not be normalized collectively.

Color-Difference Formulae

Color-difference values for all 320 stimulus comparisons were calculated using the five color-difference formulae listed below. Each of these formulae was selected for evaluation based upon previously obtained encouraging results at relating perceived color differences with calculated color difference. However, the conditions under which these formulae have previously shown promise vary significantly from the conditions of this study. Reasoning behind the selection of these color-difference formulae is briefly outlined. Specific results regarding research cited in this section were provided in the review of the literature above.

The 1976 CIELAB and CIELUV color-difference formulae, (1) and (2), were selected based upon their recommendation by the International Commission on Illumination (CIE, 1978), as well as the wide range of acceptance they receive for various applications. In addition, the 1976 CIELAB color-difference formula is the formula most commonly used by the sponsor of this research, Eastman Kodak Company, in describing color differences under similar experimental conditions.

Previous research has reported some success with the CIE equations in their ability to represent data obtained in psychophysical experiments for both small and large color-difference assessments. See Lozano (1977, 1980) and Morely, Munn, and Billmeyer (1975).

*CIE 1976 L*u*v* (CIELUV) Color-Difference Equation* (1)

ΔE^*_{uv}: $[(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2}$

where: $L^* = 116(Y/Y_n)^{1/3} - 16$
$u^* = 13L^* (u' - u'_n)$
$v^* = 13L^* (v' - v'_n)$
$u' = 4X/(X + 15Y + 3Z)$
$v' = 9Y/(X + 15Y + 3Z)$
u'_n, v'_n = the values of u', v' for the appropriate reference white.

*CIE 1976 L*a*b* (CIELAB) Color-Difference Equation* (2)

ΔE^*_{ab}: $[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$

where: $L^* = 116(Y/Y_n)^{1/3} - 16$
$a^* = 500((X/X_n)^{1/3} - Y/Y_n)^{1/3})$
$b^* = 200((Y/Y_n)^{1/3} - (Z/Z_n)^{1/3})$
X_n, Y_n, Z_n = the tristimulus values for the appropriate reference white.

The Richter and CMC (1:1) color-difference formulae, (3) and (4), were investigated based upon specific success in representing data from magnitude estimation experiments for small and large color differences in surface stimuli (Lozano, 1977, 1980; McLaren, 1986; Wood, Jacobsen, Attridge, and Pointer, 1988). While both the Richter and CMC (1:1) formulae have developed out of CIELAB color space, these two formulae initially appeared to be more successful at describing perceived color differences. The CMC (1:1) formula, in particular, calculates color differences using psychometric hue and chroma in an attempt to account for known phenomena associated with the perception of color.

Richter Color-Difference Formula (3)

$$[(\Delta L^*)^2 + (\Delta Q^*)^2 + (\Delta P^*)^2]^{1/2}$$

where: $L^* = 116(Y/Y_n)^{1/3} - 16$
$Q^* = 100Y\ (F_B)\ [q^*(F_B) - q^*(B)]$
$P^* = 100Y\ (F_B)\ [p^*(F_B) - p^*(B)]$
$q^* = p_2^{1/3}$
$p^* = p_3^{1/3}$
$p_2 = (0.35)^3(-1.99x - 2.20y + 2.40)/y$
$p_3 = (0.68)^3(8.61x + 2.80y - 0.27)/y$
F_B = Color of the Standard Stimulus
B = Color of the Comparison Stimulus

CMC(1:1) Color-Difference Formula (4)

$$[(\Delta L^*/S_L)^2 + (\Delta C^*_{ab}/S_C)^2 + (\Delta H^*_{ab}/S_H)^2]^{1/2}$$

where: $S_L = 0.040975L^*/(1 + 0.01765L^*)$
unless $L^* < 16$ when $S_L = 0.511$
$S_C = 0.0638C^*_{ab}/(1 + 0.0131C^*_{ab}) + 0.638$
$S_H = (fT + 1 - f)S_C$
$f = \{(C^*_{ab})^4/[(C^*_{ab})^4 + 1900)]\}^{1/2}$
$T = 0.36 = |0.4\cos(h_{ab} + 35)|$ unless h_{ab} is between
164 and 345 when $T = 0.56 = |0.2\cos(h_{ab} + 168)|$

The final formula , ΔE Yu´v´ (5), was included based upon its success in correlating task performance with large magnitudes of color difference for emissive display stimuli (Lippert, 1986; Martel, 1988; Sayer, Sebok, and Snyder, 1990; Schuchard, 1990a, 1990b). Although the Yu´v´ equation previously has been examined only with emissive displays, it was felt that this study provided an ideal setting in which to examine this formula using surface stimuli.

Yu´v´ Color-Legibility Metric (5)

$$[((155/Y_M)\Delta Y)^2 + (367\ \Delta u')^2 + (167\ \Delta v')^2]^{1/2}$$

where: Y = the luminance reflectance of the stimuli
Y_M = the greater of the standard/comparison luminances.
$u' = 4X/(X + 15Y + 3Z)$
$v' = 9Y/(X + 15Y + 3Z)$

RESULTS

The results portion of this thesis is partitioned into four sections, each section addressing a specific data analysis or visualization technique. The first section examines results from several analyses of covariance (ANOVA). The ANOVAs examine the effects of the independent variables in the 20 x 2 x 8 x 2 mixed-factors experimental design on the perceptually derived color-difference values, the dependent measure. The second section examines the results of linear correlation analyses which determined correlations between the dependent measure and values calculated by five color-difference formulae. The third section of the results examines multiple-regression analyses for the components of the color-difference formula determined to be most highly correlated with the perceptually derived color-difference values. The fourth, and final, section discusses the perceived moderate and large color-difference plots for each of the color regions by subject population.

Analyses of Variance

Greenhouse-Geisser correction factor. Performing an analysis of variance with repeated measures can result in positively biased F-tests. This bias is primarily the result of existing heterogeneity of covariances. A correction factor developed by Greenhouse and Geisser (1959) can be used to correct for this bias. The procedure adjusts the degrees of freedom (*df*) in both the numerator and the denominator of the F-ratio by multiplying *df* by a fractional value known as epsilon (ε). Epsilon is a measure of the extent to which variance-covariance matrices depart from assumed sphericity.

Certain conditions and limitations are associated with the Greenhouse-Geisser correction factor. First, the use of ε may, in some cases, be an over-correction resulting in a negative bias. Second, this correction is only applicable to within-subject variables for repeated measure designs. Lastly, the Greenhouse-Geisser correction factor is only used for independent measures with more than two levels, as heterogeneity of covariances cannot exist with fewer than three levels of a factor.

When appropriate, the Greenhouse-Geisser correction value, ε , is reported for independent variables in the ANOVA summary tables. Furthermore, when ε is applied, the use of the correction factor is noted in the summary tables to signify that the *p*-value shown is in fact a corrected value resulting from the Greenhouse-Geisser procedure. The analysis of variance summary tables are shown below (Tables 3 and 4). All other ANOVA tables and related post-hoc analyses for results discussed in this section are provided in Appendix D.

Experience. The main effect of EXPERIENCE on perceived color difference is statistically significant for both the Global ($F = 839.27, p < 0.0001$) and Local ($F = 10.42, p = 0.0047$) approaches to data normalization. However, it should be noted that the order of magnitude which differentiates the *F*-values between normalization approaches is considerable because the between-subjects variances differ greatly. The mean values of perceived color difference for novice and expert subjects are 1.210 and 1.371, respectively.

Table 3. ANOVA Summary Table for Global Normalization Approach

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP(Experience)	1	41.292	41.292	839.27		<0.0001
SUBJ/EXP(Subjects)	18	0.886	0.049			
Within Subjects						
COLOR(Color Region)	7	19.551	2.793	6.97	0.201	0.0078†
COLOR*EXP	7	2.882	0.412	1.03		0.4157
COLOR*SUBJ/EXP	126	50.516	0.401			
COLOR*SIZE	7	1.616	0.231	2.37	0.084	0.1502†
SIZE	1	143.490	143.490	35.97		0.0001
SIZE*EXP	1	3.598	3.598	0.90		0.3549
SIZE*SUBJ/EXP	18	71.812	3.990			
COLOR*SIZE*EXP	7	0.751	0.107	1.10		0.3670
COLOR*SIZE*SUBJ/EXP	126	12.286	0.098			
STIM/COLOR*SIZE	304	169.279	0.557	8.08	0.005	0.0035†
STIM/COLOR*SIZE*EXP	304	25.929	0.085	1.24		0.0039
STIM/COL*SIZ*SUB/EXP	5472	377.140	0.069			
Total	6399	921.029				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table 4. ANOVA Summary Table for Local Normalization Approach

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP(Experience)	1	41.736	41.736	10.42		0.0047
SUBJ/EXP(Subjects)	18	72.108	4.006			
Within Subjects						
COLOR(Color Region)	7	19.814	2.831	0.58		0.7680
COLOR*EXP	7	2.975	0.425	0.09		0.9989
COLOR*SUBJ/EXP	126	610.848	4.848			
COLOR*SIZE	7	1.643	0.235	2.61	0.084	0.1365†
SIZE	1	143.201	143.201	34.41		<0.0001
SIZE*EXP	1	3.643	3.643	0.88		0.3619
SIZE*SUBJ/EXP	18	74.920	4.162			
COLOR*SIZE*EXP	7	0.736	0.105	1.17		0.3261
COLOR*SIZE*SUBJ/EXP	126	11.347	0.090			
STIM/COLOR*SIZE	304	167.130	0.550	7.86	0.006	0.0026†
STIM/COLOR*SIZE*EXP	304	28.312	0.093	1.33		<0.0001
STIM/COL*SIZ*SUB/EX	5472	382.552	0.070			
Total	6399	1560.965				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Expert mean values shown in Table D-1 using the Global normalization approach are larger than novice means for all color regions. Note that the mean squares of the error terms (MSE) provided in the far right-hand column are all of the same relative size. The MSE values, calculated using the Student-Newman-Keuls procedure, show the variance for all color regions to be similar when the Global normalization approach is applied. Means provided in Table D-2 are, for the most part, similar with three exceptions. Because the Local approach to normalization was performed to examine variability by color region, one would not necessarily expect the MSEs to be larger than those calculated using the Global normalization approach. However, for three of the color regions (Magenta, Green, and Neutral) the MSEs are actually considerably larger.

Color region. The main effect of the within-subject variable COLOR, representing the eight color regions examined, is statistically significant for data using the Global normalization approach ($F = 6.97$, $p = 0.0078$), but not using the Local normalization approach ($F = 0.58$, $p = 0.7680$). Normalization by color region resulted in a dramatically increased COLOR*SUBJ/EXP variance. The results of a Student-Newman-Keuls (SNK) analysis showing mean values of perceived color differences after Global normalization are provided in Table D-3. As would be expected, a considerable difference exists among the color regions when data are normalized using the Global approach. However, this does not, and should not, occur with the Local normalization procedure as it eliminates such overall differences.

While color region is a significant factor, the interactions of COLOR*EXPERIENCE and COLOR*SIZE are not statistically significant. This observation is true for both approaches to data normalization. The magnitude of correction necessary to account for the heterogeneity of covariances in the COLOR*SIZE interaction dramatically affected the adjusted *p*-values for both normalization procedures. Without the application of the Greenhouse-Geisser correction results of the COLOR*SIZE interaction would be Global ($F = 2.37$, $p = 0.0263$) and Local ($F = 2.61$, $p = 0.0151$). Similar instances of small epsilon (ε) values will be seen for one additional factor, STIM/COLOR*SIZE. Exceptionally small values of ε are some cause for concern as they come close to suggesting a strongly patterned dependency in the responses across color regions.

Size. The result of the variable SIZE (5 versus 10 ΔE CIELAB) is found to be significant for both data normalization approaches. In fact, different normalization procedures appear to have little if any influence on the results of the variable SIZE. The results are virtually identical for both Global ($F = 35.97$, $p < 0.0001$) and Local ($F = 34.41$, $p < 0.0001$) approaches. The mean normalized color-difference value the 5 ΔE stimuli was 1.141, and 1.440 for 10 ΔE stimuli. However, in neither approach to normalization are the interactions of SIZE*EXPERIENCE or COLOR*SIZE*EXPERIENCE statistically significant.

Stimulus. The remaining variables of interest in the ANOVA are those which include the nested variable STIMULUS (variations in comparison

stimuli). The interaction STIMULUS/COLOR*SIZE was found to be significant for both normalization approaches. Very little difference is observed between results using the two different normalization procedures, Global approach $F = 8.08$ ($p = 0.0035$) and Local approach $F = 7.86$ ($p = 0.0026$). However, in the analyses for both normalization procedures the Greenhouse-Geisser correction procedure was suitably applied. The extremely small correction values ($\varepsilon = 0.0057$ and 0.0050) suggest that there is very large heterogeneity of covariance in the subjects' responses. The degree of apparent heterogeneity in these data leave much to be considered regarding further interpretation of the effect of color variations represented by comparison stimuli. The remaining variable of interest, STIMULUS/-COLOR*SIZE*EXPERIENCE, was also found to be significant using both normalization approaches, Global $F = 1.24$ ($p = 0.0039$) and Local $F = 1.33$ ($p < 0.0001$). However, neither the SNK nor Greenhouse-Geisser procedures could not be applied to STIMULUS/COLOR*SIZE*EXPERIENCE as it is a mixed-factor nested variable.

Examination of the individual means for the 20 levels of STIMULUS/COLOR*SIZE, or the STIMULUS/COLOR*SIZE*EXPERIENCE variable, are not particularly meaningful by themselves. Interpretation of these results is best made through examination of the perceived color-difference plots for each of the color region by size interactions separately. The color difference plots are discussed at the end of this section.

ANOVAs by color region. The final ANOVA procedures examined the variables of EXPERIENCE, SIZE, and STIMULUS/SIZE, as well as their

interactions, within each of the eight color regions. Analyses were performed separately for each color region using both normalization procedures. The results are provided in Tables D-4 though D-19 of Appendix D.

With exception of the Caucasian region, the variables of SIZE and STIMULUS/SIZE are significant factors. Results of the ANOVA for the Caucasian color region show the variable SIZE to be significant, but not STIMULUS/SIZE. Recalling the level of correction required to account for nonsphericity in the previous analyses, the Greenhouse-Geisser correction for nonsphereicity of covariances was performed on the STIMULUS/SIZE variable. The actual *p*-values are provided in ANOVA tables in Appendix D, along with the associated values of epsilon.

The final main-effects variable, EXPERIENCE, is not as easily interpreted. For six of the eight color regions examined, the results are what would have been expected based upon the outcome of the ANOVAs for all color regions collectively. Results for the Green and Neutral color regions departed considerably from that seen with other color regions. Using the Global normalization approach, the variable EXPERIENCE is significant for all color regions ($p < .05$). When the Local normalization approach is used all but the Green and Neutral color regions are significant (Tables D-7 and D-15). These results are similar to those obtained previously for EXPERIENCE employing the Local normalization approach (Table 4).

Correlation Analyses

Linear product-moment correlation analyses were performed on the normalized perceived color-difference values to determine the correlation

coefficients between perceptually derived values and those calculated by the five color-difference formulae. An analysis which used group means of the perceptually derived values rather than individual values was also performed. Analyses were performed for both methods of data normalization. The results of these correlation analyses are summarized in this section, while the remaining detailed results are provided in Appendix E. Comparisons of correlation coefficients resulting from the five color-difference equations for statistically significant differences amongst formulae were performed using the Fisher z′ transformation (Appendix E).

In reviewing all results from the correlation analyses, it was found that values calculated by the CIELAB 1976 Color-Difference Equation generally resulted in the highest levels of correlation with perceived color difference. In many instances, CIELAB provided a significantly higher correlation coefficient than did any of the remaining four equations. Therefore, the results summarized in this section compare only correlations which were observed between CIELAB and the remaining four equations. Furthermore, only correlation coefficients for group means are summarized in this section. In all cases, correlations of group mean values for perceived color difference with calculated color differences were higher than correlations with individual subject color-difference values. However, results are provided by color region for group means as well as individual subject values in Appendix E. Appendix E shows the correlation coefficients for all five formulae in comparison to one another for their ability to account for perceived color differences.

The results presented in Table 5 (Global approach) show CIELAB providing significantly better correlations with group means of perceived color-difference than were obtained for any of the remaining formulae. While CIELAB resulted in significantly better correlations for both levels of experience, responses from expert subjects were correlated significantly higher with CIELAB than were responses from novice subjects. No further differences as a result of the level of experience were seen with any of the remaining color-difference formulae.

Table 5. Correlations Coefficients of Perceived Color Difference Means with Calculated Color Differences: Global Normalization Approach - All Colors

	CIELAB	Richter	CMC(1:1)	Yu´v´	CIELUV
Novices	0.640	0.370 †	0.332 †	0.288 †	-0.126 †
Experts	0.740 §	0.467 †	0.303 †	0.316 †	-0.121 †

N = 320 † = z´, significant difference at $p \leq 0.05$ from CIELAB
§ = z´, novice vs. expert significant difference at $p \leq 0.05$

Similar results were obtained using the Local normalization approach (Table 6). While a significant difference remained between levels of experience for CIELAB, a significant difference was also seen with the Richter formula. Again, a significantly better correlation was obtained for the calculated CIELAB color-difference formula than was determined by the remaining formulae.

Table 6. Correlations Coefficients of Perceived Color Difference Means with Calculated Color Differences: Local Normalization Approach - All Colors

	CIELAB	Richter	CMC(1:1)	Yu´v´	CIELUV
Novices	0.647	0.338 †	0.320 †	0.266 †	-0.117 †
Experts	0.734 §	0.470 † *	0.291 †	0.316 †	-0.123 †

N = 320 † = z´, significant difference at $p \leq 0.05$ from CIELAB

§ = z´, novice vs. expert significant difference at $p \leq 0.05$

The correlation coefficients for all five color-difference equations were found to be significantly different form zero. However, this result is not surprising given the sample size. What is surprising is that the CIELUV color-difference metric resulted in negative correlation coefficients using both normalization approaches. While significantly less than zero, the negative correlation obtained using CIELUV certainly is not strong. Scatter plots of the results for the five color-difference equations versus perceived color difference, combining both subject groups, are provided in Figures 11 - 15. Only results utilizing data from Global normalization approach are shown. The trend of significant differences observed when all color regions are examined collectively (Tables 5 and 6) is considerably less evident when color regions are analyzed independently. Results provided in Tables 7 and 8 show correlation coefficients, by color region, for each of the color-difference formulae. Considerably fewer significant differences between correlation coefficients were found when these analyses were performed. However, in only one instance does a color-difference formula provide a value which

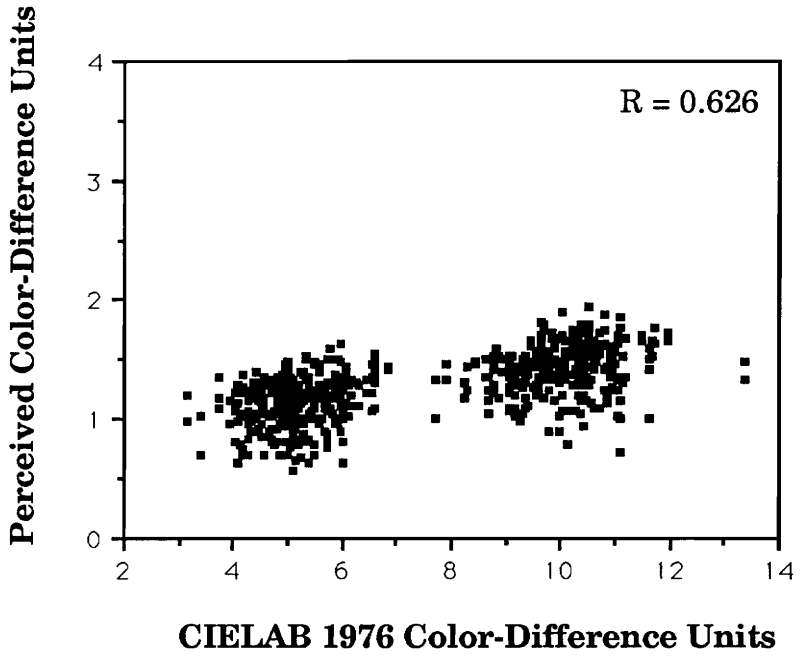


Figure 11. Perceived color difference versus CIELAB units.

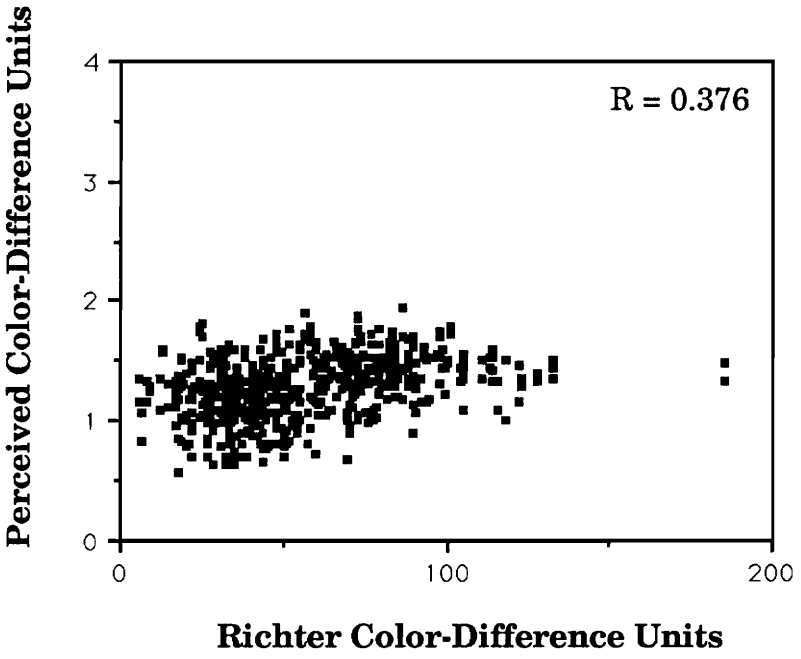


Figure 12. Perceived color difference versus Richter units.

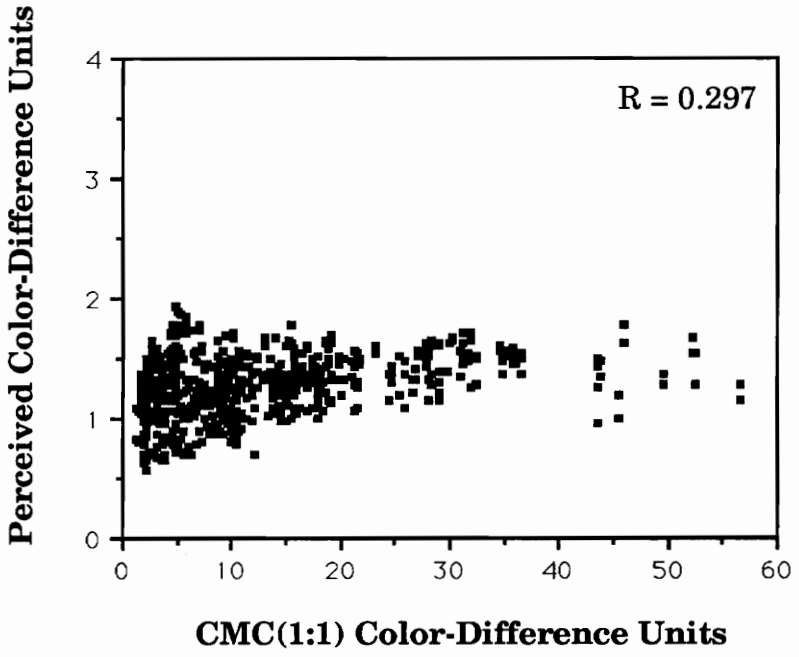


Figure 13. Perceived color difference versus CMC(1:1) units.

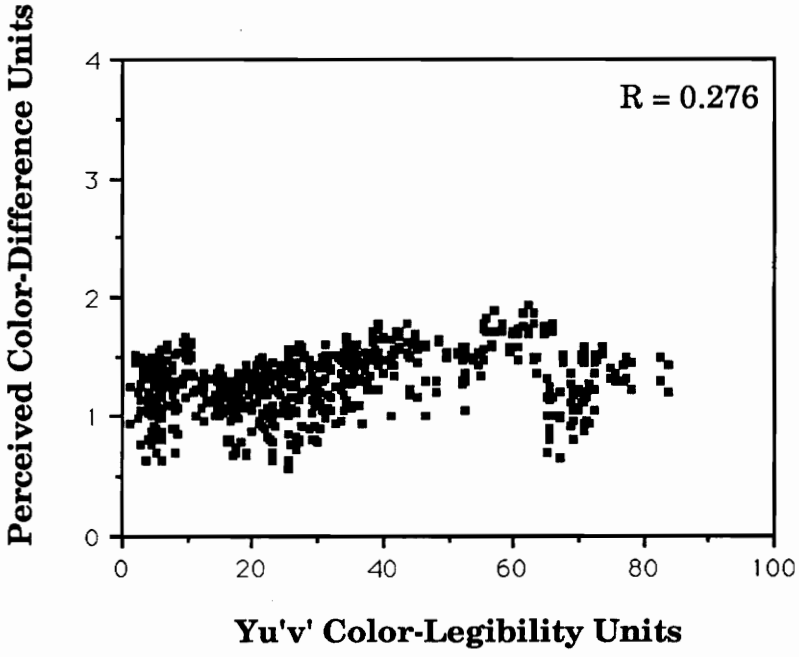


Figure 14. Perceived color difference versus Yu'v' units

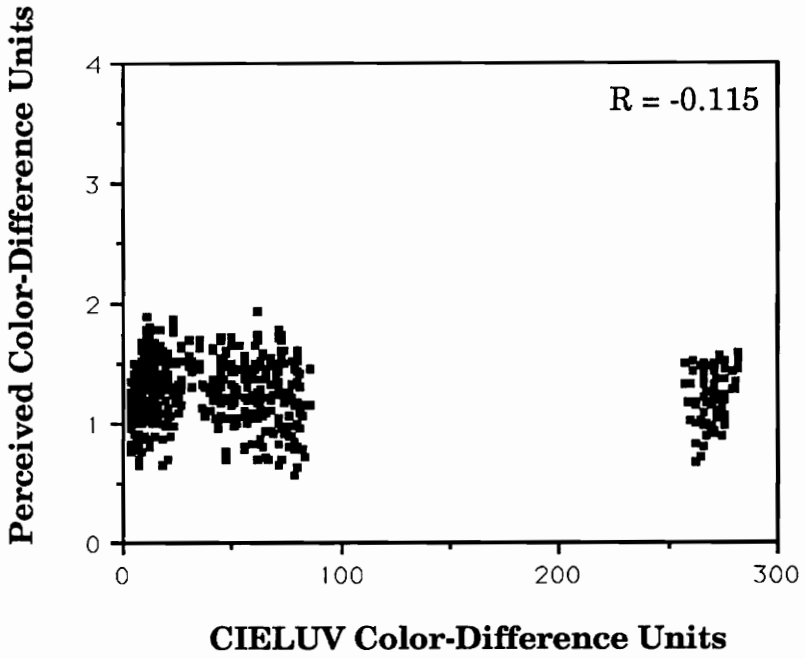


Figure 15. Perceived color difference versus CIELUV units.

Table 7. Correlations Coefficients of Perceived Color-Difference Means with Calculated Color Differences by Color Region: Global Normalization

	CIELAB	Richter	CMC(1:1)	Yu´v´	CIELUV
Magenta					
Novices	0.496	0.136	0.149	0.659	0.310
Experts	0.761 §	0.380 †	0.224 †	0.795	0.516
Green					
Novices	0.573	0.456	0.126 †	0.819 †	-0.026 †
Experts	0.705	0.548	0.250 †	0.762	0.012 †
Red					
Novices	0.834	0.493 †	0.403 †	0.620 †	-0.167 †
Experts	0.825	0.507 †	0.282 †	0.705	-0.066 †
Blue					
Novices	0.668	0.293 †	0.518	0.595	0.579
Experts	0.760	0.333 †	0.398 †	0.617	0.476 †
Yellow					
Novices	0.651	0.742	0.373	0.780	-0.214 †
Experts	0.635	0.788	0.378	0.781	-0.154 †
Neutral					
Novices	0.691	0.519	0.228 †	0.226 †	0.626
Experts	0.802	0.688	0.204 †	0.196 †	0.765
Cyan					
Novices	0.636	0.343	0.183 †	0.683	0.100 †
Experts	0.750	0.446 †	0.193 †	0.739	0.009 †
Caucasian					
Novices	0.847	0.632 †	0.602 †	0.377 †	0.306 †
Experts	0.844	0.625 †	0.523 †	0.422 †	0.207 †

N = 40 † = z´, significant difference at $p \leq 0.05$ from CIELAB

§ = z´, novice vs. expert significant difference at $p \leq 0.05$

Table 8. Correlations Coefficients of Perceived Color-Difference Means with Calculated Color Differences by Color Region: Local Normalization

	CIELAB	Richter	CMC(1:1)	Yu´v´	CIELUV
Magenta					
Novices	0.495	0.135	0.149	0.659	0.310
Experts	0.762 §	0.380 †	0.224 †	0.795	0.517
Green					
Novices	0.573	0.456	0.126 †	0.819 †	-0.026 †
Experts	0.705	0.548	0.250 †	0.762	0.012 †
Red					
Novices	0.834	0.493 †	0.403 †	0.620 †	-0.167 †
Experts	0.825	0.508 †	0.282 †	0.705	-0.066 †
Blue					
Novices	0.667	0.293 †	0.518	0.595	0.579
Experts	0.760	0.333 †	0.397 †	0.618	0.476 †
Yellow					
Novices	0.650	0.414	0.603	0.216 †	-0.173 †
Experts	0.635	0.788 §	0.378	0.781 §	-0.154 †
Neutral					
Novices	0.691	0.519	0.227 †	0.226 †	0.627
Experts	0.803	0.688	0.204 †	0.196 †	0.765
Cyan					
Novices	0.636	0.344	0.183 †	0.683	0.100 †
Experts	0.738	0.432 †	0.139 †	0.749	0.027 †
Caucasian					
Novices	0.848	0.633 †	0.602 †	0.377 †	0.306 †
Experts	0.809	0.655	0.458 †	0.393 †	0.110 †

N = 40 † = z´, significant difference at $p \leq 0.05$ from CIELAB

§ = z´, novice vs. expert significant difference at $p \leq 0.05$

results in a correlation coefficient significantly higher than that provided by CIELAB (Local approach, green color region, novice subjects, Yu´v´ metric).

The negative correlations observed for all color regions collectively with the CIELUV color-difference metric are found to be extremely dependent upon the color region examined. Results provided in Tables 7 and 8 for the CIELUV metric show a broad range of values across the eight color regions. No other color-difference metric resulted in correlation coefficients for which the range varied so greatly as did CIELUV.

Results of intercorrelation analyses, providing correlation coefficients between calculated color-difference values for the different equations, are shown in Table 9.

Table 9. Intercorrelation Analyses between Calculated Color-Difference Values

	CIELAB	Richter	CMC(1:1)	Yu'v'
CIELUV	-0.02046 0.6053	0.26821 0.0001 †	-0.04467 0.2592	0.74247 0.0001 †
CIELAB		0.70385 0.0001 †	0.30562 0.0001 †	0.25730 0.0001 †
Richter			0.31712 0.0001 †	0.27233 0.0001 †
CMC(1:1)				-0.16741 0.0001 †

N = 640 † = Prob > |R|, were R is significantly greater than zero.

Multiple Regression

Of the five formulae investigated, the CIELAB Color-Difference Equation was found to consistently provide higher levels of correlation with perceived color differences. It would therefore be useful to understand how individual components which make up the CIELAB equation contribute to the observed levels of correlation. Multiple-regression analyses were performed to examine how the absolute values of individual components in the CIELAB equation correlate with perception of moderate and large color differences. CIELAB Metric Hue and Metric Chroma difference values were also calculated and included in the regression analyses.

Results of the multiple-regression analyses shown in Tables 10 and 11 report correlation coefficients (r). Once again, Fisher's z´ transformations were calculated in order that significant differences existing between levels of subject experience could be identified. It must be recognized that the variables included in the model were taken out of context of the CIELAB color-difference equation. However, one would certainly expect that trends identified in these results are worthy of further investigation.

Using the Global normalization approach, the only significant difference between novice and expert color judges is for the model which included the variables L*, C*, and H*. No significant differences between the two models of L*, C*, H* and L*, a*, b* exist within either subject population. The component values prior to being incorporated into the linear equation account for most of, and in some cases more, of the explained variance when one compares them to the CIELAB correlation coefficients as reported in Tables 5 and 6. Similar results can be observed for multiple-regression analyses of

CIELAB with perceived color-difference group means employing the Local normalization approach (Table 11). While several additional models resulted in significant difference between subject populations using the Local normalization approach, no significant difference between the two models of L* ,C*, H* and L*, a*, b* is observed.

Perceived Moderate and Large Color-Difference Plots

Plots presented in Appendix F show the perceptually rescaled three-dimensional spaces for each of the eight color regions, two levels of color-difference, and two subject groups. Points located on the surfaces represent those points listed in Table 2 and shown in Figure 3. The distance from the origin for a color region is the mean of the perceived color differences for the stimulus representing that point in CIELAB color space. Color differences used in the generation of these plots were normalized using the Local approach. Where replicates exist in the design, the mean of the two perceived color differences, after normalization, is plotted. All plots are drawn to the same scale. Therefore, comparisons between points within the entire color space for any color region can be made directly. Axes are provided to indicate the direction in which plots are projected. For reference purposes, all points shown in the plots of Appendix F are identified in an idealized plot where the distance from the origin is a constant (Figure 12).

The perceived color-difference plots provided in Appendix F show a wide variety of responses to the comparison stimuli. Plots vary not only in size as a result of the level of color differences examined (5 ΔE versus 10 ΔE), but also by color region and experience levels. While considerable similarity in

Table 10. Multiple-Regression Analyses: Correlation Coefficients for Novice vs. Expert Subjects - Global Normalization Approach

Novice	Expert	Variable(s) in Model	z´ Score
0.558	0.603	L*	0.855
0.250	0.260	H*	0.135
0.203	0.248	a*	0.597
0.064	0.074	b*	0.127
-0.045	0.007	C*	0.655
0.722	0.774	L*, H*	1.491
0.632	0.684	L*, a*	1.156
0.581	0.629	L*, b*	0.954
0.578	0.643	L*, C*	1.307
0.261	0.261	C*, H*	0.000
0.228	0.277	a*, b*	0.659
0.739	0.806	L*, C*, H*	2.105 †
0.677	0.748	L*, a*, b*	1.824

N = 320 † Novice vs. expert difference significant at $p \leq 0.05$

Table 11. Multiple Regression Analyses: Correlation Coefficients for Novice vs. Expert Subjects - Local Normalization Approach

Novice	Expert	Variable(s) in Model	z´ Scores
0.485	0.605	L*	1.868
0.284	0.245	H*	0.528
0.225	0.242	a*	0.226
0.110	0.064	b*	0.584
0.013	0.008	C*	0.063
0.674	0.767	L*, H*	2.455 †
0.574	0.684	L*, a*	2.305 †
0.523	0.646	L*, b*	2.366 †
0.520	0.629	L*, C*	2.057 †
0.285	0.268	C*, H*	0.232
0.276	0.245	a*, b*	0.419
0.701	0.799	L*, C*, H*	2.853 †
0.638	0.744	L*, a*, b*	2.576 †

N = 320 † Novice vs. expert difference significant at $p \leq 0.05$

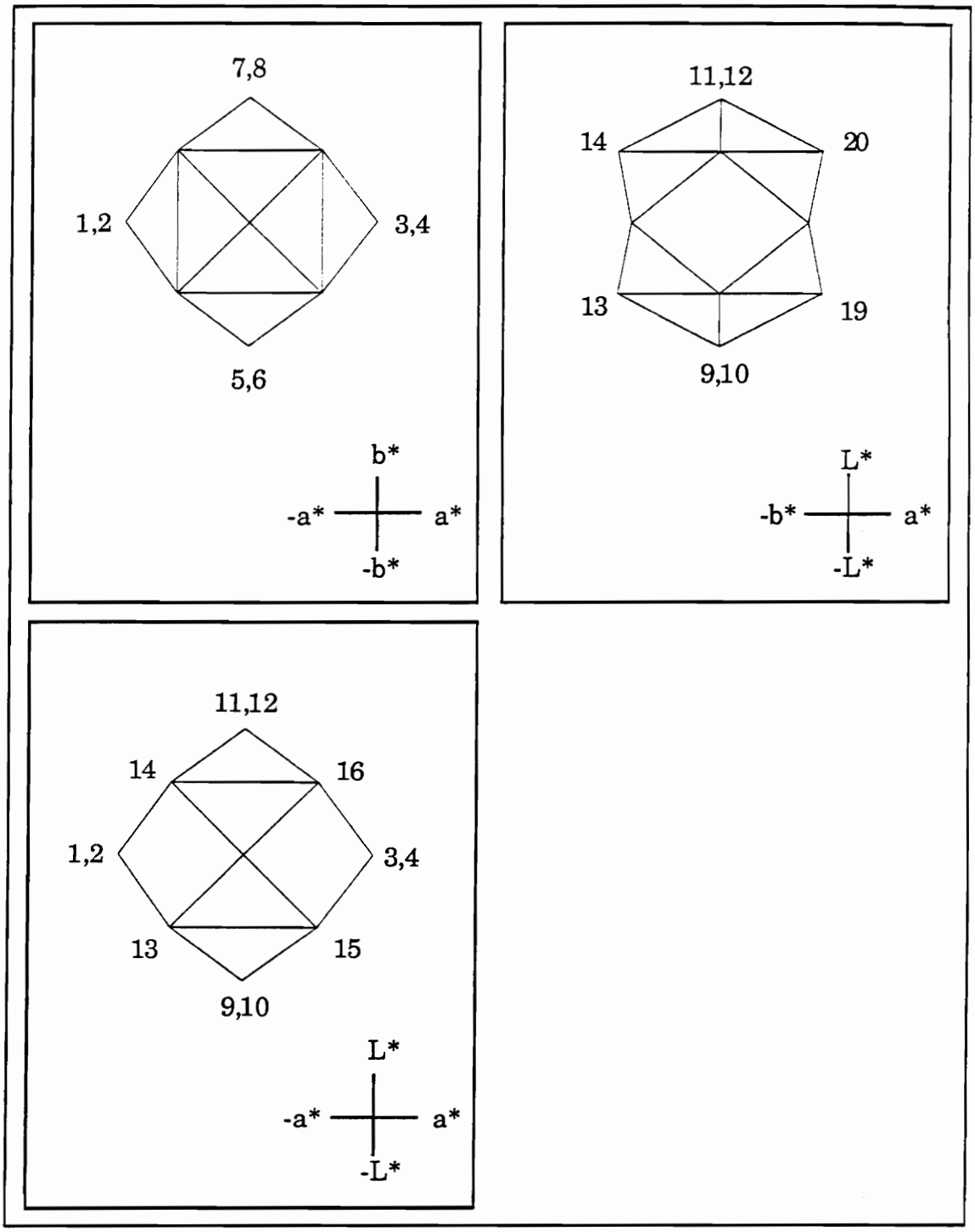


Figure 16. Shape of an ideal perceived color-difference plot.

color-difference plots exists between novice and expert subjects for some color regions (Neutral, Green 10 ΔE, and Cyan 10 ΔE), plots of other regions are strikingly different (Yellow 5 ΔE). The most dramatic differences in color-difference plot size and shape are observed across color regions.

The one attribute most all of the color-difference plots have in common is that they are elongated on the L* axis, relative to a* and b* axes. The only color region in which this L* elongation is not observed is for the Neutral color region. Almost all color-difference plots appear to differ considerably in shape from the idealized plot shown in Figure 12. However, plots of perceived color differences for experts continually appear to be more similar to the idealized plot, for all color regions, than do those of novice subjects.

DISCUSSION

Analyses of Variance

For the most part, the analyses of variance results are not surprising. Prior to the investigation it had been anticipated that the variables SIZE and COLOR would be significant. However, the statistically significant differences observed between levels of EXPERIENCE were not anticipated. Nonetheless, the results are consistent in showing that a difference exists between the way in which novice and expert subjects perceive moderate and large color differences. Based upon previous investigations, a difference due to experience would not have been predicted. Since an expert is not physically any more capable of perceiving color differences, past experience in making this type of visual assessment apparently provided experts with internalized criteria on which to base color-differences.

Experience. The differences observed between levels of experience, novice versus expert, are particularly strong. While previous investigations on the effects of training in color-difference assessment would predict a considerably different outcome, one point dramatically differentiates the results of this study from previous investigations. Experienced subjects participating in this study were not trained solely for purposes of collecting data. Expert subjects were experienced via their occupation in performing color-difference assessments. Research previously reported by Indow and Matsushima (1974), as well as Indow and Watanabe (1980), examined the effects of short-term training more so than experience.

While a significant difference between novice and expert subjects is observed for all color regions using the Global normalization procedure, EXPERIENCE level is not a significant factor for two color regions using the Local approach. What remains unexplained is why for the Green and Neutral color regions novice and expert subjects appear to perceive differences in a similar fashion. An explanation is made difficult given that the variability of subject responses to stimuli in the Neutral region was so large relative to other color regions (Table D-2).

One explanation for the Neutral region result is possible biasing from use of a neutral colored modulus set. It is conceivable that the stimuli in the modulus set may have aided some subjects, while distracting others, in both groups in providing color-difference assessments for stimuli in the Neutral region. Examination of the perceived color-difference plots shows a striking similarity in shape between levels of EXPERIENCE for the Neutral color region (Figures F-21 though F-24). Similarity in plot shapes for the Green color region is also evident (Figures F-5 though F-8). However, both groups of subjects reported perceived color differences in the Neutral and Green color regions with a much greater degree of variability. No immediate explanation is offered for the observed MSEs for either color region.

Color region. The variables examining color region, COLOR, and magnitude of the color difference, SIZE, are somewhat more easily interpreted than the EXPERIENCE variables. As anticipated, and necessarily forced through normalization, the application of the Local normalization procedure did not result in significant differences among the

levels of the variable COLOR. However, significant differences among color regions are present using the Global normalization approach. Through the application of the Local normalization approach, the variance associated with use of different values per color region was eliminated (intra-subject or intra-region variance). Inter-subject variability, variation associated with the use of different modulus set values across subjects, was eliminated by performing either of the normalization procedures.

While use of the Local approach is beneficial toward understanding how subjects perceive large color differences, most color-difference equations are not particularly sensitive to differences associated with specific regions of color space. The difference between the outcomes from the two normalization procedures appears to be perceptual variability associated with different color regions of CIELAB color space. This result lends support to the idea that CIELAB is not perceptually uniform. Perhaps there is even sufficient evidence to warrant the rescaling of CIELAB color space to account for existing nonuniformities. One needs only to examine the variation in size and shape of the perceived color-difference plots to see the degree of nonuniformity which exists across color regions.

Although rescaling has been suggested by previous investigators (Morely et al., 1975; Post et al., 1983; Stalmeier and de Weert, 1988), it is difficult to rescale for every type of experimental condition in which color-difference equations are used. This approach is an insurmountable task when one considers the numerous factors known to affect color perception. However, certainly some applications could justify the level of effort required to rescale CIELAB color space. If conditions for use of a rescaled color space can be

specified and adhered to, then rescaling for particular applications might be warranted. Otherwise, too many variables are involved when considering all factors affecting the perception of color differences.

While the independent variable COLOR is a significant factor, the interactions of COLOR*SIZE and COLOR*EXPERIENCE are not. Although the nonsignificant result of the COLOR*EXPERIENCE interaction is somewhat of a surprise, the fact that the COLOR*SIZE interaction is not significant was quite unexpected. In examining the color-difference plots, one might quickly draw the conclusion that the COLOR*SIZE interaction variance is quite large. However, the degree of heterogeneity of covariance impacted this result considerably. The apparent dependency of responses across color regions provides further evidence in support of attempts at rescaling CIELAB color space.

Size. Results for the independent variable SIZE are not affected by either of the normalization procedures. Using both normalization procedures, the magnitude of the color difference, 5 ΔE versus 10 ΔE CIELAB, resulted in significant differences for all color regions. While the outcome is not surprising, the magnitude of the perceived differences is not on the order that one might have expected. If CIELAB color space were perceptually uniform, one could expect to see a linear relationship maintained between the magnitude of perceived differences and calculated differences. However, examination of the perceived color-difference plots in Appendix F suggests that the magnitudes of perceived color difference are not linearly related.

Scaling the distances from the origin, points representing the perception of 5 ΔE color differences are considerably more than half the distance to comparable 10 ΔE points. While some previous investigations concerning the perception of large color differences employed similar methodologies and analyses, to the best of the author's knowledge none maintained criteria as stringent as those held in this investigation. Previous investigators (Mattiello and Guirao, 1974a and 1974b; Lozano, 1977, 1980; and Morely et al., 1975) reported similar results for the effect of color-difference magnitude. However, questions persist as to whether the same findings would have resulted had stimuli been uniform in magnitude of color difference across various regions in color space.

Surprisingly, for neither approach to normalization are the interactions of SIZE*EXPERIENCE or COLOR*SIZE*EXPERIENCE significant in the overall ANOVAs. However, SIZE*EXPERIENCE is a significant factor for several of the ANOVAs performed by color region (Tables D-4 though D-19). In viewing the perceived color-difference plots in Appendix F, values reported by experts appear larger than those offered by novices. Even for the Neutral color region where subjects may have been biased through the use of a neutral colored modulus, expert subject values resulted in plots of larger perceived color difference (Figures F-21 though F-24).

Stimulus. Results for the STIMULUS/COLOR*SIZE interaction are significant in the ANOVAs across all color regions regardless of the normalization procedure used. The variable STIMULUS/SIZE is also significant for seven of the eight color regions examined. Although a

dramatically high level of nonsphericity was corrected for in the overall ANOVAs, even after the correction procedure was applied the results remained significant. Further analyses of the STIMULUS/COLOR*SIZE variable did not produce any conclusive results. Because the variable has 20 levels, and is nested, interpretation of the results other than to observe general trends cannot be reliably performed. This interpretation could have been made considerably easier, and more meaningful, had the comparison stimuli been identified and analyzed with respect to hue angle of the individual color regions. Otherwise, the most meaningful interpretation of results with regards to the variable STIMULUS is made through examination of the perceived color-difference plots on a region-by-region basis.

Correlation Analyses

The results from the linear correlation analyses are fairly consistent in showing that CIELAB color space is better correlated with perceived color differences than any of the remaining four equations, despite its apparent perceptual nonuniformities. This result is observed for both levels of subject experience and most color regions. Furthermore, the performance of CIELAB across all color regions was significantly better than other formulae for either normalization approach.

Although the correlation coefficients obtained using CIELAB color-difference values were not exceptionally large, moderate correlations offer a certain degree of promise. Furthermore, only moderatly high correlations

resulted for any of the analyses. However, the linearity of the data is fairly apparent, with examples being provided in Figures 11 thru 15.

When it was developed and recommended for the use by the International Commission on Illumination, the CIELAB 1976 Color Difference Equation was not intended to be a perceptually uniform color space. Instead, CIELAB and CIELUV were attempts at encouraging uniformity of color measurement throughout industry. The fact that CIELAB is at least as good as, and in this application better than, CIELUV is encouraging, especially since the CIELAB equation is used in the photographic industry. However, questions remain.

First, why is the CIELUV color-difference metric poorly correlated with perceived moderate and large color differences in photographic prints? Second, are there other color-difference formulae that have not been examined which are more highly correlated with perceived color differences for the conditions examined?

While no particular explanation is offered as to why the CIELUV color-difference metric performed so poorly in this study, the fact that a very limited region of color space was actually examined might reveal some answers. Of course the same could be said for all of the color-difference metrics examined. While several different color regions were investigated, only one relative lightness plane ($L^* = 53$) was studied. Before general statements regarding the correlation between perceived and calculated color differences can be made for any of the metrics examined, further investigation into various perceived lightness regions is warranted.

Multiple Regression Analyses

Results of multiple-regression analyses on the components of the CIELAB color-difference equation show the L* component to independently account for more variance than any of the remaining variables in the model. The L* component continues to contribute a considerable amount to all remaining models in which it is included. However, L* does not significantly account for more variance than do the remaining independent components in the model. The importance of perceived lightness variation in the stimuli can easily be seen in the perceived color-difference plots. For all but one color region, Neutral, the perceived color-difference plots have considerably elongated L* axes.

Addition of the psychometric hue and chroma components to the regression analyses did not produce any unexpected results relative to those observed using the standard CIELAB components. While they did not contribute to the models as much as the L* component, C* and H* appear to perform important roles as do the a* and b* components. Interestingly, the C* and H* components contribute to models in which significant differences are observed more frequently between novice and expert subjects when the Local normalization approach is performed.

The components of all five color-difference equations were not examined in a similar fashion as their calculated differences did not show much promise in the linear correlation analyses. While it might be informative to do so at a later date, caution must be emphasized when examining these present results. The variables included in the multiple-regression models are taken

dramatically out of the context of the original equations and generalizable conclusions should not be draw from these results alone.

Perceived Moderate and Large Color-Difference Plots

While plotting may be the simplest of analysis techniques, for this application it is perhaps the most informative. The plots of perceived color differences in Appendix F show the perceptual nonuniformity of CIELAB color space. Upon examination, these plots support the results of earlier analysis techniques as well as provide information regarding the perception of specific stimuli in various color regions.

If CIELAB color space is perceptually uniform, the calculated color differences, CIELAB ΔE units, which separate the experimental stimuli should produce perceptually rescaled color-difference plots similar to the reference (Figure 12). Deviation from this idealized three-dimensional form is either the result of the tolerances allowed in generating the stimuli (+/- 2 ΔE CIELAB units) or the fact that CIELAB color space is not perceptually uniform.

Plotting of the normalized perceived color differences produced an elongation of the axis representing perceived lightness. The lengthening of the L* axis over the a* and b* axes occurs for all but one color region (Neutral). Lengthening of the L* axis indicates that while stimuli are of the same relative color difference (CIELAB ΔE), both populations of subjects perceive variation in lightness to be greater than along either of the other two dimensions. This result supports that which was observed in the multiple-regression analyses. The fact that the Neutral region is not elongated on the

L* axis, but is in fact foreshortened, suggests that perceived color differences which subjects report for the Neutral region may be influenced by the use of a neutral colored modulus set, particularly when one considers that the modulus set itself varied only along the L* dimension.

In general, the most obvious conclusion to be drawn from the perceived color-difference plots is that CIELAB color space is not perceptually uniform in estimating perceived color differences for color photographic prints. The variability in size and shape of the perceived color-difference plots across color regions is considerable. Further variability in size and shape between novice and expert subjects is also evident. However, again it should be noted that the stimuli examined in this study represent a limited proportion of CIELAB color space and only moderate and large color differences were investigated.

CONCLUSIONS

The results of this study support the preference of the CIELAB 1976 Color-Difference Equation over other metrics examined for predicting the perception of moderate and large color differences in photographic print material. Under the conditions examined, CIELAB frequently resulted in significantly better predictions of the magnitude of color difference that subjects perceived between two stimuli. While other color-difference metrics provided higher correlations in limited instances, in only one condition was another metric significantly better than CIELAB. For the type of stimuli and regions of color space examined, the CIELAB color-difference metric provides the best overall predictive capabilities of the five metrics.

While evidence was found that novice and expert subjects perceive moderate and large color differences in a somewhat different manner, specific differences appear to be limited to the degree of sensitivity to change and not to the use of separate criteria. However, the CIELAB color-difference equation resulted only in moderate correlations for both experienced and non-experienced color-difference judges when all color regions were examined. Higher correlation coefficients were observed for some color regions when they were examined separately. This suggests that a better understanding of perceived color spaces might be reached if color regions are addressed separately.

While the applicability of these results is limited to the range of stimuli investigated, under the conditions of examination, there appears to be sufficient evidence to warrant further studies. Specifically, stimuli

representing other perceived lightness levels should be investigated. In addition, knowledge of the possible effects of variations in viewing conditions and use of small color differences might prove to be very beneficial.

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APPENDIX A - Location of Stimuli in CIELAB Color Space

Table A-1. Location of Stimuli in CIELAB Color Space - Magenta

a*	b*	L*	Stimulus
23.933	-14.644	53.816	1
24.106	-14.315	53.892	2
33.951	-14.909	53.929	3
34.219	-15.242	54.603	4
28.601	-19.891	54.694	5
29.104	-19.651	54.848	6
29.326	-9.244	53.430	7
29.383	-8.912	53.538	8
29.328	-14.660	49.111	9
29.760	-14.073	50.387	10
28.446	-14.098	59.148	11
28.609	-14.100	59.437	12
25.682	-17.506	50.658	13
25.673	-17.651	57.724	14
25.553	-10.475	50.247	15
25.827	-11.482	57.247	16
31.914	-17.436	50.849	17
31.632	-17.649	57.063	18
31.097	-10.441	50.949	19
31.048	-11.201	57.298	20
18.654	-14.620	53.646	21
18.571	-15.299	53.300	22
38.807	-15.083	54.467	23
38.575	-14.811	54.329	24
28.652	-25.005	53.482	25
28.783	-24.763	54.392	26
28.382	-4.828	53.725	27
28.469	-5.301	54.238	28
27.549	-15.197	43.868	29
27.663	-14.992	44.140	30
28.275	-14.001	64.386	31
28.439	-14.074	64.292	32
23.739	-20.525	47.630	33
22.625	-19.961	60.180	34
22.665	-8.506	47.575	35
22.420	-7.701	60.123	36
34.849	-20.090	48.442	37
34.958	-20.362	61.694	38
35.390	-8.426	48.443	39
34.435	-7.106	60.113	40

Table A-2. Location of Stimuli in CIELAB Color Space - Green

a*	b*	L*	Stimulus
-25.847	23.624	52.928	1
-26.760	22.667	52.919	2
-16.801	22.366	53.864	3
-16.699	22.535	53.724	4
-21.714	17.403	53.553	5
-21.668	17.130	52.809	6
-21.765	27.629	53.807	7
-21.826	27.124	53.862	8
-21.931	22.058	47.563	9
-22.052	21.990	48.016	10
-21.347	22.004	57.206	11
-21.219	21.821	57.543	12
-24.947	19.389	49.679	13
-25.139	18.000	56.192	14
-24.213	25.098	50.480	15
-25.130	25.051	55.938	16
-19.099	19.672	50.366	17
-19.536	19.428	55.722	18
-18.889	25.989	49.179	19
-18.653	25.571	55.509	20
-30.703	21.533	53.921	21
-30.998	21.482	53.364	22
-11.631	23.017	52.670	23
-11.646	22.736	53.164	24
-21.496	13.512	52.710	25
-21.894	12.867	53.100	26
-21.750	33.152	54.685	27
-21.867	33.215	54.566	28
-22.051	23.498	43.084	29
21.976	23.817	43.409	30
-20.503	22.400	62.721	31
-20.665	22.221	62.896	32
27.927	16.127	47.124	33
-27.007	16.661	58.410	34
-27.689	27.950	47.137	35
26.535	28.352	58.807	36
16.409	15.968	47.413	37
-16.492	16.328	58.416	38
-15.607	28.274	48.176	39
-15.509	28.472	58.728	40

Table A-3. Location of Stimuli in CIELAB Color Space - Red

a*	b*	L*	Stimulus
20.494	8.332	53.633	1
20.769	8.411	54.171	2
29.866	7.158	53.040	3
29.926	6.984	53.545	4
25.023	2.168	53.422	5
24.695	1.947	54.141	6
25.695	13.004	52.709	7
25.888	13.463	52.643	8
26.273	8.013	47.645	9
26.754	7.738	48.774	10
25.689	7.607	57.554	11
25.651	6.880	57.508	12
22.196	4.936	49.716	13
23.236	5.083	56.979	14
23.005	10.533	50.583	15
22.767	11.033	55.617	16
28.098	5.211	50.208	17
28.131	4.096	56.923	18
28.618	10.145	49.596	19
28.172	11.023	55.931	20
15.738	7.664	52.628	21
15.864	7.655	53.040	22
34.912	7.263	53.716	23
34.709	6.768	53.554	24
24.872	-3.047	53.037	25
25.591	-2.826	53.307	26
25.907	17.599	52.715	27
26.192	17.815	53.186	28
25.203	7.946	42.781	29
25.157	7.868	43.246	30
25.468	7.990	64.007	31
25.446	7.618	63.691	32
19.860	1.941	45.839	33
19.498	1.762	58.797	34
19.178	14.703	46.644	35
20.119	13.983	57.962	36
31.282	2.195	46.506	37
31.925	3.083	59.039	38
31.717	14.278	48.155	39
30.221	13.637	59.252	40

Table A-4. Location of Stimuli in CIELAB Color Space - Blue

a*	b*	L*	Stimulus
-8.321	-17.168	53.262	1
-8.561	-16.953	53.796	2
1.404	-17.339	53.326	3
1.821	-16.779	53.514	4
-3.562	-23.012	54.119	5
-3.497	-23.261	54.503	6
-2.802	-12.827	54.198	7
-3.156	-12.660	54.408	8
-3.054	-17.264	48.367	9
-2.711	-17.203	49.594	10
-3.507	-17.416	59.101	11
-3.325	-17.368	58.883	12
-6.532	-19.838	51.355	13
-6.599	-20.592	57.082	14
-5.715	-13.377	49.701	15
-6.087	-14.224	56.250	16
-.162	-20.082	50.979	17
-.975	-20.932	56.591	18
.764	-13.832	49.970	19
-.087	-14.342	56.370	20
-12.957	-17.646	54.680	21
-13.165	-18.226	53.427	22
7.335	-17.202	54.253	23
7.346	-17.782	54.725	24
-5.205	-27.156	53.935	25
-4.854	-27.219	53.549	26
-3.299	-7.939	54.278	27
-3.416	-8.152	53.972	28
-4.563	-16.801	44.115	29
-4.287	-17.055	44.093	30
-3.043	-16.747	64.291	31
-2.986	-16.717	64.025	32
-9.753	-23.822	47.167	33
-10.522	-23.898	60.105	34
-10.165	-10.975	46.482	35
-8.422	-11.780	59.643	36
1.890	-23.564	48.156	37
.984	-23.324	60.795	38
2.562	-12.320	49.572	39
3.263	-11.347	58.888	40

Table A-5. Location of Stimuli in CIELAB Color Space - Yellow

a*	b*	L*	Stimulus
17.312	42.957	53.665	1
17.370	43.365	53.523	2
17.583	43.823	53.552	3
17.515	43.612	53.547	4
17.526	38.805	53.730	5
12.310	38.307	52.833	6
12.712	48.698	52.963	7
13.208	49.579	53.996	8
12.768	42.944	47.560	9
12.945	43.687	47.599	10
12.398	42.827	57.613	11
11.982	42.546	57.776	12
9.452	40.143	50.516	13
9.622	41.417	56.204	14
10.679	47.225	50.677	15
10.083	45.158	56.875	16
15.867	40.601	50.363	17
16.086	40.096	55.756	18
15.927	47.762	51.815	19
15.297	45.956	57.973	20
2.638	43.179	52.200	21
2.442	42.828	52.021	22
21.705	43.509	53.215	23
21.329	43.218	53.984	24
12.015	33.232	52.935	25
12.421	33.861	53.052	26
12.551	53.777	53.454	27
12.763	54.672	54.286	28
12.168	44.552	43.195	29
12.264	44.117	42.938	30
12.058	43.790	63.058	31
12.043	43.545	63.246	32
6.353	37.903	47.106	33
6.799	38.139	58.580	34
5.997	49.247	47.055	35
6.063	48.880	58.547	36
17.804	37.502	47.349	37
18.506	37.797	59.268	38
18.046	50.200	48.046	39
17.968	49.393	59.964	40

Table A-6. Location of Stimuli in CIELAB Color Space - Neutral

a*	b*	L*	Stimulus
-4.247	2.984	55.594	1
-4.094	3.116	54.966	2
5.801	2.799	55.208	3
5.854	3.138	55.316	4
1.453	-2.237	55.382	5
1.731	-2.398	55.625	6
1.292	8.255	54.572	7
1.458	8.590	54.761	8
.708	2.759	49.298	9
.659	3.040	49.573	10
1.609	3.048	59.702	11
1.575	2.473	60.363	12
-2.435	-.568	52.481	13
-1.675	-.391	58.429	14
-1.684	5.595	51.794	15
-1.805	4.949	57.578	16
3.830	-.241	52.783	17
3.944	-.803	58.202	18
4.103	6.322	51.416	19
4.901	6.233	57.983	20
-8.659	2.409	55.238	21
-8.621	2.279	55.727	22
10.572	2.472	54.757	23
10.376	2.222	54.739	24
1.463	-7.628	55.237	25
1.391	-7.809	55.895	26
1.055	13.139	54.616	27
.702	12.990	54.880	28
.903	2.424	45.066	29
1.085	2.452	44.753	30
1.789	3.520	64.748	31
1.724	3.464	65.166	32
-5.349	-2.392	49.291	33
-4.383	-3.146	60.284	34
-4.055	7.157	48.607	35
-3.708	8.638	61.463	36
7.811	-3.068	49.254	37
8.020	-3.012	60.309	38
7.702	9.204	49.397	39
7.135	8.084	60.391	40

Table A-7. Location of Stimuli in CIELAB Color Space - Cyan

a*	b*	L*	Stimulus
-25.378	-12.020	52.448	1
-25.108	-11.742	52.933	2
-16.471	-11.170	53.143	3
-16.640	-11.760	53.000	4
-21.249	-17.115	54.026	5
-20.995	-16.748	54.208	6
-21.194	-6.729	52.592	7
-21.045	-6.999	52.947	8
-21.617	-11.686	47.821	9
-21.340	-11.607	48.617	10
-20.766	-10.702	57.603	11
-20.637	-10.393	58.415	12
-24.198	-15.211	49.526	13
-23.724	-15.271	55.865	14
-23.309	-8.074	49.149	15
-23.194	-8.203	55.996	16
-18.292	-14.438	50.574	17
-17.821	-14.318	56.299	18
-18.113	-8.988	50.303	19
-17.337	-7.428	55.588	20
-30.089	-12.636	52.898	21
-29.807	-12.599	53.737	22
-10.632	-10.239	52.521	23
-10.804	-10.511	52.523	24
-21.424	-20.048	53.847	25
-21.456	-20.313	53.682	26
-20.858	-2.286	52.671	27
-20.735	-2.617	52.837	28
-20.540	-11.726	42.459	29
-20.314	-11.460	42.768	30
-16.863	-14.892	66.948	31
-16.591	-14.374	67.837	32
-28.782	-20.142	44.680	33
-25.818	-17.748	59.850	34
-26.175	-6.841	45.415	35
-25.797	-6.288	59.783	36
-15.990	-17.838	47.232	37
-15.190	-17.476	60.123	38
-13.128	-2.180	43.353	39
-14.120	-4.941	58.434	40

Table A-8. Location of Stimuli in CIELAB Color Space - Caucasian

a*	b*	L*	Stimulus
12.003	18.067	68.400	1
12.122	17.904	68.809	2
22.194	18.354	68.702	3
22.050	18.487	69.242	4
17.276	13.003	68.112	5
17.212	13.072	68.184	6
17.809	24.202	68.321	7
17.851	24.091	68.250	8
17.226	18.090	63.103	9
17.172	17.805	63.210	10
14.509	14.159	62.580	11
14.445	14.037	62.745	12
13.427	16.358	65.629	13
15.281	13.882	71.302	14
16.401	21.454	67.079	15
16.012	21.271	70.560	16
19.714	16.131	64.558	17
20.512	17.258	70.540	18
20.753	20.598	67.160	19
20.180	22.712	70.783	20
7.069	18.108	67.986	21
7.101	17.854	68.316	22
26.678	18.012	67.324	23
26.550	17.857	67.851	24
17.545	8.203	68.125	25
17.464	7.972	68.835	26
18.007	26.508	68.808	27
18.181	27.069	68.777	28
17.165	18.159	59.763	29
17.221	18.132	60.148	30
16.388	17.445	78.097	31
16.098	17.087	78.560	32
11.128	12.688	63.178	33
11.549	12.354	73.252	34
11.707	23.795	62.895	35
11.546	24.063	73.739	36
22.105	12.559	63.272	37
23.340	12.495	74.126	38
23.352	24.086	62.876	39
16.580	30.027	77.833	40

APPENDIX B - Informed Consent Form

PARTICIPANTS INFORMED CONSENT

Title of study: Color Difference Study

Researcher: James R. Sayer

Brief Description

The experiment in which you are about to participate will require you to provide subjective opinions regarding differences between colored patches. The purpose of this study is to determine how individuals perceive color differences.

Before you are permitted to participate in the study, you will be required to take part in a tests for visual sensitivity and color discrimination. These tests require a high degree of sensitivity, and you may be excused from the study by the investigator after completing these tests. If you are excused from the experiment after the vision test, you will be paid $4.00 for your time. The testing session will last approximately 40 minutes.

The study itself will last approximately four to six hours, and will be divided into four sessions. During these sessions you will give your subjective opinion of differences which exist between colored stimuli. During the course of the experiment you will be in no way subjected to any known risks of harm or injury. Short periodic breaks will be permitted during the sessions if you so choose to take them.

Consent

You have now read a brief description of this experiment and understand that its purpose is to assess differences between color patches. You will receive $5.00 an hour for participating in the study, and $4.00 for the testing session. A bonus of $5 will be awarded if you arrive at your scheduled appointments on time, and you complete the sessions.

If you have any questions regarding this experiment you may contact the researcher at 231-9092. You may also contact the Faculty Research Advisor for this project, Dr. H. L. Snyder, at 231-7527, or the University Institutional Review Board Chairman, Dr. E.R. Stout, at 231-5281.

As a participant in this experiment, you have certain rights, as listed below. You should read and understand these rights prior to your consenting to participate in this study.

1) You have the right to stop participating in this experiment at any time.

2) You have the right to withdraw your data from the experiment. All data are treated anonymously. Therefore, if you wish to withdraw your data, you must indicate so before leaving the session.

3) You have the right to be informed of the overall results of this experiment. If you wish to receive information about the results, please include your address with your signature below. If you do so, a summary will be sent to you approximately three months after completion of the study. For further information you may contact the Human Factors Laboratory and a full report will be made available to you.

4) There are no known risks or discomforts associated with your participation in this experiment.

Your signature below indicates that you understand what is expected of you in this study, and that you have read the above stated rights and consent to participate.

Printed name	Signature	Date

APPENDIX C - Instructions to Subjects

INSTRUCTIONS

Introduction

Thank you for volunteering to participate in this color difference study. You have been selected to participate in this study based upon your ability to discriminate differences between colors, as determined during the screening session. Please read the instructions carefully and examine the video taped demonstrations. Feel free to ask questions at any time. Instructions will be reviewed with you prior to beginning the study.

The goal of this study is to determine how people perceive differences between colors. There will be no right or wrong responses during any portion of the study. Throughout, you will be asked to provide your subjective assessment of how color samples differ from one another. It is important that you provide responses which are representative of what you actually perceive, as opposed to what you might think the experimenter wants to hear.

At this time, please put on the pair of cotton gloves and grey lab coat we have provided you.

Using round colored patches, similar to those which are located in front of you, you will be asked to compare the individual patches located at the bottom of the board with the patch mounted in the center of the board (the standard patch). You are to make these comparisons <u>one at a time</u>. At no time should you compare more than one patch with the standard. You

should, however, examine the range of patches provided to you to the right of the black line without making direct comparisons patches.

Comparisons should be made by sliding the individual patches up to the raised surface on which the standard is mounted. Patches should at no time be lifted off the board's surface. Therefore, a space will always separate the individual patch from the standard patch.

Please stop to examine the stimuli placed in front of you at this time.

Establishing a Reference

The first task you are asked to preform is similar, though slightly different, to the remainder of the study. This first task is important in that it will set the tone and establish a reference for you to use while making all judgements for the remainder of the study. Therefore, please pay close attention to the following instructions.

Position yourself in front of the board, resting your forehead against the headrest provided. You must maintain this position whenever you are comparing patches.

Using the patches in front of you, compare the individual patches to the standard mounted in the center of the board. For each comparison, you are to

report a numerical value which you feel represents the magnitude of the difference between the individual patch and the standard. The only restriction is that this value be a positive whole number (no fractions please). This means you may choose any number between zero (0) and infinity, including zero. A response of zero (0) would correspond to there being no perceptible difference between the patch and the standard.

After having made comparisons for each of the individual patches, and assigning values, place each of the patches in the order in which you performed the comparisons. This is only for the purposes of allowing the experimenter to record your responses. There is no set order in which you are to compare the individual color patches.

You may take your time in performing this task to ensure you are comfortable with the values you assign.

Please stop at this point to establish the reference set of stimuli.

The Color Difference Study

Now that you have assigned values to the reference set of patches, these patches will be labelled with your responses and left where you can refer back to them at any time during the remainder of the study. In fact, you are encouraged to use this reference set, and the relative values you have

assigned, in making all further comparisons. The purpose of the reference set is to allow you to provide similar responses to differences which you perceive to be similar in magnitude throughout the duration of the study.

From this point on you will perform a comparable task. There will be more patches, however the procedure is virtually the same as it was for the reference set. Please remember to always do the following:

- Wear the cotton gloves and lab coat when touching the patches.

- Maintain a posture with your head against the headrest while making comparisons.

- Compare only one patch to the standard mounted in the center of the board at a time.

- Assign a numerical value, taking into consideration the references set you specified, and report that number to the experimenter.

- Place each of the individual color patches off to the side in the order in which you make the comparison and assign the values.

Please remember to refer back to the reference set when making your comparisons, and speak clearly when reporting the values you assign. Again,

there are no right or wrong responses. Simply try to be consistent in assigning numerical values to the relative differences you perceive to exist.

Please stop at this point to examine the videotaped demonstration.

Do you have any questions at this time?

APPENDIX D - Analysis of Variance Tables

Table D-1. Mean Values for the Variable EXPERIENCE by Color Region, Global Normalization Approach

Color Region	Mean	N	Experience	MSE
Magenta	1.353	400	Expert	0.049
	1.144	400	Novice	
Green	1.344	400	Expert	0.233
	1.181	400	Novice	
Red	1.392	400	Expert	0.354
	1.277	400	Novice	
Blue	1.417	400	Expert	0.483
	1.294	400	Novice	
Yellow	1.326	400	Expert	0.913
	1.087	400	Novice	
Neutral	1.412	400	Expert	0.228
	1.277	400	Novice	
Cyan	1.402	400	Expert	0.496
	1.281	400	Novice	
Caucasian	1.325	400	Expert	0.082
	1.138	400	Novice	

Table D-2. Mean Values for the Variable EXPERIENCE by Color Region, Local Normalization Approach

Color Region	Mean	N	Experience	MSE
Magenta	1.353	400	Expert	0.436
	1.144	400	Novice	
Green	1.344	400	Expert	3.150
	1.181	400	Novice	
Red	1.392	400	Expert	5.584E-6
	1.277	400	Novice	
Blue	1.417	400	Expert	2.819E-6
	1.294	400	Novice	
Yellow	1.326	400	Expert	3.595E-6
	1.087	400	Novice	
Neutral	1.412	400	Expert	34.356
	1.277	400	Novice	
Cyan	1.402	400	Expert	3.502E-6
	1.281	400	Novice	
Caucasian	1.325	400	Expert	0.0001
	1.138	400	Novice	

Table D-3. Student-Newman-Keuls Test of the Variable COLOR, Global Normalization Approach

SNK Grouping			Mean	N	COLOR
A			1.355	800	Blue
A	B		1.344	800	Neutral
A	B		1.341	800	Cyan
A	B		1.334	800	Red
	B	C	1.262	800	Green
		C	1.251	800	Magenta
		C	1.232	800	Caucasian
		C	1.206	800	Yellow

Means with the same letter are not significantly different. $p > 0.05$.

Table D-4. Analysis of Variance Table for Global Normalization Approach - Magenta Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP (Experience)	1	8.303	8.303	35.68		<0.0001
SUBJ/EXP	18	4.189	0.233			
Within Subjects						
SIZE	1	16.445	16.445	149.51		<0.0001
SIZE*EXP	1	0.041	0.041	0.37		0.5431
SIZE*SUBJ/EXP	18	5.140	0.285			
STIM/SIZE	38	25.686	0.676	6.15	0.037	0.0121 †
STIM/SIZE*EXP	38	6.400	0.168	1.53		0.0230
STIM/SIZE*SUBJ/EXP	684	75.238	0.110			
Total	799	141.443				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-5. Analysis of Variance Table for Local Normalization Approach - Magenta Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	8.749	8.749	20.06		0.0003
SUBJ/EXP	18	7.852	0.436			
Within Subjects						
SIZE	1	16.445	16.445	149.51		<0.0001
SIZE*EXP	1	0.041	0.041	0.37		0.5431
SIZE*SUBJ/EXP	18	5.140	0.285			
STIM/SIZE	38	25.686	0.676	6.15	0.037	0.0121 †
STIM/SIZE*EXP	38	6.400	0.168	1.53		0.0230
STIM/SIZE*SUBJ/EXP	684	75.238	0.110			
Total	799	145.552				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-6. Analysis of Variance Table for Global Normalization Approach - Green Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP (Experience)	1	5.311	5.311	77.05		<0.0001
SUBJ/EXP	18	1.241	0.069			
Within Subjects						
SIZE	1	14.371	14.371	188.14		<0.0001
SIZE*EXP	1	0.429	0.429	5.62		0.0180
SIZE*SUBJ/EXP	18	5.983	0.332			
STIM/SIZE	38	31.652	0.833	10.90	0.039	0.0009 †
STIM/SIZE*EXP	38	4.226	0.111	1.46		0.0397
STIM/SIZE*SUBJ/EXP	684	52.249	0.076			
Total	799	115.462				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-7. Analysis of Variance Table for Local Normalization Approach - Green Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	5.323	5.323	1.69		0.2100
SUBJ/EXP	18	56.701	3.150			
Within Subjects						
SIZE	1	14.372	14.372	183.51		<0.0001
SIZE*EXP	1	0.429	0.429	5.48		0.0195
SIZE*SUBJ/EXP	18	6.029	0.335			
STIM/SIZE	38	31.653	0.833	10.64	0.039	0.0010 †
STIM/SIZE*EXP	38	4.225	0.111	1.42		0.0510
STIM/SIZE*SUBJ/EXP	684	53.570	0.078			
Total	799	172.303				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-8. Analysis of Variance Table for Global Normalization Approach - Red Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	2.666	2.666	7.56		0.0132
SUBJ/EXP	18	6.350	0.353			
Within Subjects						
SIZE	1	21.285	21.285	475.79		<0.0001
SIZE*EXP	1	0.828	0.828	18.50		<0.0001
SIZE*SUBJ/EXP	18	10.733	0.596			
STIM/SIZE	38	12.862	0.338	7.57	0.042	0.0040 †
STIM/SIZE*EXP	38	1.839	0.048	1.08		0.3423
STIM/SIZE*SUBJ/EXP	684	30.600	0.045			
Total	799	87.164				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-9. Analysis of Variance Table for Local Normalization Approach - Red Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	2.647	2.647	>1000		<0.0001
SUBJ/EXP	18	$0.001E^{-1}$	$0.006E^{-3}$			
Within Subjects						
SIZE	1	21.285	21.285	475.79		<0.0001
SIZE*EXP	1	0.828	0.828	18.50		<0.0001
SIZE*SUBJ/EXP	18	10.733	0.596			
STIM/SIZE	38	12.862	0.338	7.57	0.042	0.0040 †
STIM/SIZE*EXP	38	1.839	0.048	1.08		0.3423
STIM/SIZE*SUBJ/EXP	684	30.600	0.045			
Total	799	80.796				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-10. Analysis of Variance Table for Global Normalization Approach - Blue Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	3.010	3.010	6.24		0.0224
SUBJ/EXP	18	8.688	0.483			
Within Subjects						
SIZE	1	19.214	19.214	270.30		<0.0001
SIZE*EXP	1	0.722	0.722	10.15		0.0015
SIZE*SUBJ/EXP	18	15.761	0.876			
STIM/SIZE	38	19.305	0.508	7.15	0.037	0.0073 †
STIM/SIZE*EXP	38	3.517	0.092	1.30		0.1087
STIM/SIZE*SUBJ/EXP	684	48.622	0.071			
Total	799	118.839				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-11. Analysis of Variance Table for Local Normalization Approach - Blue Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	3.020	3.020	>1000		<0.0001
SUBJ/EXP	18	$0.005E^{-2}$	$0.003E^{-3}$			
Within Subjects						
SIZE	1	19.214	19.214	270.30		<0.0001
SIZE*EXP	1	0.722	0.722	10.15		0.0015
SIZE*SUBJ/EXP	18	15.761	0.876			
STIM/SIZE	38	19.305	0.508	7.15	0.037	0.0073 †
STIM/SIZE*EXP	38	3.517	0.092	1.30		0.1087
STIM/SIZE*SUBJ/EXP	684	48.622	0.071			
Total	799	110.161				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-12. Analysis of Variance Table for Global Approach Normalization - Yellow Color Region

Source	*df*	*SS*	*MS*	*F*	*ε*	*p*
Between Subjects						
EXP	1	11.401	11.401	12.49		0.0024
SUBJ/EXP	18	16.429	0.913			
Within Subjects						
SIZE	1	23.231	23.231	432.08		<0.0001
SIZE*EXP	1	1.153	1.153	21.45		<0.0001
SIZE*SUBJ/EXP	18	23.195	1.288			
STIM/SIZE	38	31.386	0.826	15.36	0.041	<0.0001 †
STIM/SIZE*EXP	38	2.331	0.061	1.14		0.2609
STIM/SIZE*SUBJ/EXP	684	36.776	0.054			
Total	799	145.904				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-13. Analysis of Variance Table for Local Normalization Approach - Yellow Color Region

Source	*df*	*SS*	*MS*	*F*	*ε*	*p*
Between Subjects						
EXP	1	11.420	11.420	>1000		<0.0001
SUBJ/EXP	18	$0.006E^{-2}$	$0.004E^{-3}$			
Within Subjects						
SIZE	1	23.231	23.231	432.08		<0.0001
SIZE*EXP	1	1.153	1.153	21.45		<0.0001
SIZE*SUBJ/EXP	18	23.195	1.289			
STIM/SIZE	38	31.386	0.826	15.36	0.041	<0.0001 †
STIM/SIZE*EXP	38	2.331	0.061	1.14		0.2609
STIM/SIZE*SUBJ/EXP	684	36.776	0.054			
Total	799	129.493				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-14. Analysis of Variance Table for Global Normalization Approach - Neutral Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	3.632	3.632	15.93		0.0009
SUBJ/EXP	18	4.104	0.228			
Within Subjects						
SIZE	1	12.797	12.797	203.65		<0.0001
SIZE*EXP	1	0.084	0.084	1.34		0.2474
SIZE*SUBJ/EXP	18	3.471	0.193			
STIM/SIZE	38	13.663	0.359	5.72	0.040	0.0135 †
STIM/SIZE*EXP	38	2.153	0.057	0.90		0.6412
STIM/SIZE*SUBJ/EXP	684	42.984	0.063			
Total	799	82.888				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-15. Analysis of Variance Table for Local Normalization Approach - Neutral Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	3.658	3.658	0.11		0.7480
SUBJ/EXP	18	618.401	34.356			
Within Subjects						
SIZE	1	12.796	12.796	186.03		<0.0001
SIZE*EXP	1	0.084	0.084	1.22		0.2691
SIZE*SUBJ/EXP	18	5.616	0.312			
STIM/SIZE	38	13.664	0.360	5.23	0.040	0.0182 †
STIM/SIZE*EXP	38	2.154	0.057	0.82		0.7664
STIM/SIZE*SUBJ/EXP	684	47.051	0.069			
Total	799	703.425				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-16. Analysis of Variance Table for Global Normalization Approach - Cyan Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	2.897	2.897	5.85		0.0264
SUBJ/EXP	18	8.921	0.496			
Within Subjects						
SIZE	1	14.864	14.864	186.53		<0.0001
SIZE*EXP	1	0.188	0.188	2.36		0.1248
SIZE*SUBJ/EXP	18	3.564	0.198			
STIM/SIZE	38	27.595	0.726	9.11	0.043	0.0015 †
STIM/SIZE*EXP	38	3.749	0.099	1.24		0.1577
STIM/SIZE*SUBJ/EXP	684	54.505	0.080			
Total	799	116.284				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-17. Analysis of Variance Table for Local Normalization Approach - Cyan Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	2.931	2.931	>1000		<0.0001
SUBJ/EXP	18	$0.006E^{-2}$	$0.004E^{-3}$			
Within Subjects						
SIZE	1	14.602	14.602	183.16		<0.0001
SIZE*EXP	1	0.219	0.219	2.75		0.0978
SIZE*SUBJ/EXP	18	3.541	0.197			
STIM/SIZE	38	27.507	0.724	9.08	0.043	0.0016 †
STIM/SIZE*EXP	38	4.068	0.107	1.34		0.0844
STIM/SIZE*SUBJ/EXP	684	54.529	0.080			
Total	799	107.397				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-18. Analysis of Variance Table for Global Normalization Approach - Caucasian Color Region

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	6.954	6.954	84.52		<0.0001
SUBJ/EXP	18	1.481	0.082			
Within Subjects						
SIZE	1	22.897	22.897	433.06		<0.0001
SIZE*EXP	1	0.904	0.904	17.09		<0.0001
SIZE*SUBJ/EXP	18	16.251	0.903			
STIM/SIZE	38	7.129	0.188	3.55	0.040	0.0539 †
STIM/SIZE*EXP	38	1.714	0.045	0.85		0.7214
STIM/SIZE*SUBJ/EXP	684	36.165	0.053			
Total	799	93.495				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

Table D-19. Analysis of Variance Table for Local Normalization Approach - Caucasian Color Region.

Source	*df*	*SS*	*MS*	*F*	ε	*p*
Between Subjects						
EXP	1	6.962	6.962	>1000		<0.0001
SUBJ/EXP	18	0.002	$0.001E^{-1}$			
Within Subjects						
SIZE	1	22.897	22.897	433.06		<0.0001
SIZE*EXP	1	0.904	0.904	17.09		<0.0001
SIZE*SUBJ/EXP	18	16.251	0.903			
STIM/SIZE	38	5.066	0.133	2.52	0.040	0.1108 †
STIM/SIZE*EXP	38	3.778	0.099	1.88		0.0013
STIM/SIZE*SUBJ/EXP	684	36.165	0.053			
Total	799	92.024				

† *p*-values corrected for sphericity (Greenhouse and Geisser, 1959).

APPENDIX E - Fisher's z´ Transformation Tables

Global Normalization Approach

Table E-1. Correlations of Perceived Color Differences with Calculated Color Differences: Global Normalization Approach - All Colors

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.417	0.250	0.198	0.184
L*u*v*	-0.076	29.443*	18.795*	15.647*	14.834*
L*a*b*	0.417		10.647*	13.796*	14.609*
Richter	0.250			3.148*	3.961*
CMC 1:1	0.198				0.813
Yu´v´	0.184				

N = 6400 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.382	0.221	0.198	0.172
L*u*v*	-0.075	19.091*	11.982*	11.051*	9.956*
L*a*b*	0.382		7.110*	8.041*	9.136*
Richter	0.221			0.931	2.026*
CMC 1:1	0.198				1.095
Yu´v´	0.172				

N = 3200 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.640	0.404	0.262	0.273
L*u*v*	-0.105	34.518*	21.348*	14.945*	15.408*
L*a*b*	0.640		13.171*	19.574*	19.110*
Richter	0.404			6.403*	5.939*
CMC 1:1	0.262				0.464
Yu´v´	0.273				

N = 3200 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.075	1.191	-0.105
L*a*b*	0.382	14.236*	0.640
Richter	0.221	8.175*	0.404
CMC 1:1	0.198	2.703*	0.262
Yu´v´	0.172	4.262*	0.273

N = 3200 * z´ score significant at $p \leq 0.05$

Table E-2. Correlations of Perceived Color Differences with Calculated Color Differences: Global Normalization Approach - Magenta

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.338	0.129	0.101	0.403
L*u*v*	0.220	2.557*	1.878	2.447*	4.069*
L*a*b*	0.338		4.435*	5.004*	1.512
Richter	0.129			0.569	5.947*
CMC 1:1	0.101				6.516*
Yu´v´	0.403				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.276	0.075	0.083	0.367
L*u*v*	0.173	1.531	1.393	1.283	2.961*
L*a*b*	0.276		2.924*	2.814*	1.430
Richter	0.075			0.109	4.354*
CMC 1:1	0.083				4.245*
Yu´v´	0.367				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.652	0.325	0.192	0.681
L*u*v*	0.442	4.282*	1.932	3.951*	5.010*
L*a*b*	0.652		6.214*	8.233*	0.728
Richter	0.325			2.019*	6.942*
CMC 1:1	0.192				8.961*
Yu´v´	0.681				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.173	4.231*	0.442
L*a*b*	0.276	6.982*	0.652
Richter	0.075	3.692*	0.325
CMC 1:1	0.083	1.564	0.192
Yu´v´	0.367	6.280*	0.681

N = 400 * z´ score significant at $p \leq 0.05$

Table E-3. Correlations of Perceived Color Differences with Calculated Color Differences: Global Normalization Approach - Green

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.397	0.313	0.110	0.510
L*u*v*	-0.008	8.553*	6.619*	2.353*	11.402*
L*a*b*	0.397		1.934	6.200*	2.849*
Richter	0.313			4.266*	4.784*
CMC 1:1	0.110				9.050*
Yu´v´	0.510				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.367	0.292	0.081	0.525
L*u*v*	-0.017	5.663*	4.471*	1.378	8.444*
L*a*b*	0.367		1.193	4.285*	2.780*
Richter	0.292			3.092*	3.973*
CMC 1:1	0.081				7.066*
Yu´v´	0.525				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.602	0.467	0.213	0.650
L*u*v*	0.010	9.657*	6.993*	2.905*	10.781*
L*a*b*	0.602		2.664*	6.752*	1.124
Richter	0.467			4.088*	3.788*
CMC 1:1	0.213				7.876*
Yu´v´	0.650				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.017	0.380	0.010
L*a*b*	0.367	4.373*	0.602
Richter	0.292	2.902*	0.467
CMC 1:1	0.081	1.907	0.213
Yu´v´	0.525	2.717*	0.650

N = 400 * z´ score significant at $p \leq 0.05$

Table E-4. Correlations of Perceived Color Differences with Calculated Color Differences: Global Normalization Approach - Red

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.529	0.318	0.226	0.417
L*u*v*	-0.081	13.370*	8.182*	6.199*	10.465*
L*a*b*	0.529		5.189*	7.171*	2.905*
Richter	0.318			1.983*	2.283*
CMC 1:1	0.226				4.266*
Yu´v´	0.417				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.506	0.299	0.244	0.376
L*u*v*	-0.101	9.289*	5.779*	4.945*	7.004*
L*a*b*	0.506		3.511*	4.344*	2.286*
Richter	0.299			0.833	1.225
CMC 1:1	0.244				2.058*
Yu´v´	0.376				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.712	0.438	0.243	0.608
L*u*v*	-0.057	13.357*	7.415*	4.297*	10.751*
L*a*b*	0.712		5.941*	9.060*	2.606*
Richter	0.438			3.119*	3.336*
CMC 1:1	0.243				6.454*
Yu´v´	0.608				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.101	0.636	-0.057
L*a*b*	0.506	4.703*	0.712
Richter	0.299	2.273*	0.438
CMC 1:1	0.244	0.013	0.243
Yu´v´	0.376	4.383*	0.608

N = 400 * z´ score significant at $p \leq 0.05$

Table E-5. Correlations of Perceived Color Differences with Calculated Color Differences: Global Normalization Approach - Blue

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.409	0.179	0.275	0.352
L*u*v*	0.315	2.178*	2.884*	0.863	0.828
L*a*b*	0.409		5.062*	3.041*	1.349
Richter	0.179			2.021*	3.712*
CMC 1:1	0.275				1.691
Yu´v´	0.352				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.372	0.163	0.289	0.332
L*u*v*	0.323	0.791	2.397*	0.530	0.142
L*a*b*	0.372		3.189*	1.322	0.650
Richter	0.163			1.867	2.539*
CMC 1:1	0.289				0.672
Yu´v´	0.332				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.660	0.289	0.345	0.536
L*u*v*	0.413	4.974*	2.003*	1.122	2.232*
L*a*b*	0.660		6.977*	6.096*	2.742*
Richter	0.289			0.880	4.234*
CMC 1:1	0.345				3.354*
Yu´v´	0.536				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.323	1.478	0.413
L*a*b*	0.372	5.661*	0.660
Richter	0.163	1.873	0.289
CMC 1:1	0.289	0.886	0.345
Yu´v´	0.332	3.568*	0.536

N = 400 * z´ score significant at $p \leq 0.05$

Table E-6. Correlations of Perceived Color Differences with Calculated Color Differences: Global Normalization Approach - Yellow

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.399	0.470	0.232	0.483
L*u*v*	-0.118	10.786*	12.549*	7.074*	12.868*
L*a*b*	0.399		1.763	3.712*	2.082*
Richter	0.470			5.475*	0.320
CMC 1:1	0.232				5.794*
Yu´v´	0.483				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.391	0.446	0.224	0.469
L*u*v*	-0.128	7.643*	8.576*	5.032*	8.980*
L*a*b*	0.391		0.933	2.611*	1.337
Richter	0.446			3.544*	0.404
CMC 1:1	0.224				3.948*
Yu´v´	0.469				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.562	0.697	0.334	0.691
L*u*v*	-0.137	10.894*	14.088*	6.839*	13.926*
L*a*b*	0.562		3.194*	4.055*	3.032*
Richter	0.697			7.249*	0.162
CMC 1:1	0.334				7.087*
Yu´v´	0.691				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	**z´ score**	**Expert**
L*u*v*	-0.128	0.125	-0.137
L*a*b*	0.391	3.126*	0.562
Richter	0.446	5.387*	0.697
CMC 1:1	0.224	1.682	0.334
Yu´v´	0.469	4.822*	0.691

N = 400 * z´ score significant at $p \leq 0.05$

Table E-7. Correlations of Perceived Color Differences with Calculated Color Differences: Global Normalization Approach - Cyan

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.427	0.342	0.126	0.124
L*u*v*	0.396	0.739	1.270	5.839*	5.887*
L*a*b*	0.427		2.009*	6.578*	6.626*
Richter	0.342			4.569*	4.617*
CMC 1:1	0.126				0.048
Yu´v´	0.124				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.372	0.280	0.123	0.122
L*u*v*	0.338	0.558	0.900	3.218*	3.230*
L*a*b*	0.372		1.458	3.776*	3.788*
Richter	0.280			2.318*	2.330*
CMC 1:1	0.123				0.012
Yu´v´	0.122				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.678	0.582	0.173	0.166
L*u*v*	0.647	0.791	1.480	8.393*	8.487*
L*a*b*	0.678		2.271*	9.184*	9.278*
Richter	0.582			6.913*	7.007*
CMC 1:1	0.173				0.094
Yu´v´	0.166				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.338	5.895*	0.647
L*a*b*	0.372	6.128*	0.678
Richter	0.280	5.315*	0.582
CMC 1:1	0.123	0.720	0.173
Yu´v´	0.122	0.638	0.166

N = 400 * z´ score significant at $p \leq 0.05$

Table E-8. Correlations of Perceived Color Differences with Calculated Color Differences: Global Normalization Approach - Neutral

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.420	0.237	0.116	0.433
L*u*v*	0.040	8.141*	4.020*	1.520	8.459*
L*a*b*	0.420		4.121*	6.621*	0.317
Richter	0.237			2.500*	4.439*
CMC 1:1	0.116				6.939*
Yu´v´	0.433				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.374	0.202	0.108	0.401
L*u*v*	0.059	4.700*	2.050*	0.688	5.160*
L*a*b*	0.374		2.651*	4.013*	0.460
Richter	0.202			1.362	3.110*
CMC 1:1	0.108				4.472*
Yu´v´	0.401				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.647	0.385	0.167	0.630
L*u*v*	0.007	10.749*	5.611*	2.273*	10.347*
L*a*b*	0.647		5.137*	8.476*	0.402
Richter	0.385			3.338*	4.735*
CMC 1:1	0.167				8.074*
Yu´v´	0.630				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	**z´ score**	**Expert**
L*u*v*	0.059	0.730	0.007
L*a*b*	0.374	5.319*	0.647
Richter	0.202	2.832*	0.385
CMC 1:1	0.108	0.856	0.167
Yu´v´	0.401	4.457*	0.630

N = 400 * z´ score significant at $p \leq 0.05$

Table E-9. Correlations of Perceived Color Differences with Calculated Color Differences: Global Normalization Approach - Caucasian

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.489	0.364	0.330	0.228
L*u*v*	0.154	7.577*	4.510*	3.744*	1.536
L*a*b*	0.489		3.067*	3.833*	6.041*
Richter	0.364			0.766	2.974*
CMC 1:1	0.330				2.208*
Yu´v´	0.228				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.476	0.356	0.339	0.212
L*u*v*	0.172	4.859*	2.794*	2.521*	0.589
L*a*b*	0.476		2.065*	2.338*	4.270*
Richter	0.356			0.274	2.206*
CMC 1:1	0.339				1.932
Yu´v´	0.212				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.706	0.523	0.438	0.353
L*u*v*	0.173	9.932*	5.709*	4.150*	2.738*
L*a*b*	0.706		4.224*	5.782*	7.194*
Richter	0.523			1.559	2.971*
CMC 1:1	0.438				1.412
Yu´v´	0.353				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.172	0.016	0.173
L*a*b*	0.476	5.089*	0.706
Richter	0.356	2.930*	0.523
CMC 1:1	0.339	1.645	0.438
Yu´v´	0.212	2.165*	0.353

N = 400 * z´ score significant at $p \leq 0.05$

Global Normalization Approach - Mean Values

Table E-10. Correlations of Perceived Color Differences Means with Calculated Color Differences: Global Normalization Approach - All Colors

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.626	0.376	0.297	0.276
L*u*v*	-0.115	15.179*	9.112*	7.514*	7.108*
L*a*b*	0.626		6.066*	7.665*	8.070*
Richter	0.376			1.599	2.004*
CMC 1:1	0.297				0.405
Yu´v´	0.276				

N = 640 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.640	0.370	0.332	0.288
L*u*v*	-0.126	11.134*	6.481*	5.944*	5.328*
L*a*b*	0.640		4.653*	5.190*	5.806*
Richter	0.370			0.536	1.153
CMC 1:1	0.332				0.617
Yu´v´	0.288				

N = 320 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.740	0.467	0.303	0.316
L*u*v*	-0.121	13.488*	7.909*	5.471*	5.647*
L*a*b*	0.740		5.579*	8.017*	7.841*
Richter	0.467			2.438*	2.262*
CMC 1:1	0.303				0.176
Yu´v´	0.316				

N = 320 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.126	0.064	-0.121
L*a*b*	0.640	2.418*	0.740
Richter	0.370	1.492	0.467
CMC 1:1	0.332	0.409	0.303
Yu´v´	0.288	0.383	0.316

N = 320 * z´ score significant at $p \leq 0.05$

Table E-11. Correlations of Perceived Color Differences Means with Calculated Color Differences: Global Normalization Approach - Magenta

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.533	0.203	0.159	0.636
L*u*v*	0.347	1.441	0.966	1.251	2.415*
L*a*b*	0.533		2.407*	2.692*	0.974
Richter	0.203			0.285	3.381*
CMC 1:1	0.159				3.666*
Yu´v´	0.636				

N = 80 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.496	0.136	0.149	0.659
L*u*v*	0.310	0.957	0.793	0.733	2.020*
L*a*b*	0.496		1.750	1.689	1.064
Richter	0.136			0.061	2.814*
CMC 1:1	0.149				2.753*
Yu´v´	0.659				

N = 40 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.761	0.380	0.224	0.795
L*u*v*	0.516	1.843	0.735	1.476	2.214*
L*a*b*	0.761		2.579*	3.319*	0.370
Richter	0.380			0.741	2.949*
CMC 1:1	0.224				3.690*
Yu´v´	0.795				

N = 40 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.310	1.075	0.516
L*a*b*	0.496	1.962*	0.761
Richter	0.136	1.134	0.380
CMC 1:1	0.149	0.332	0.224
Yu´v´	0.659	1.269	0.795

N = 40 * z´ score significant at $p \leq 0.05$

Table E-12. Correlations of Perceived Color Differences Means with Calculated Color Differences: Global Normalization Approach - Green

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.571	0.449	0.157	0.733
L*u*v*	-0.011	4.094*	3.073*	1.053	5.874*
L*a*b*	0.571		1.021	3.040*	1.781
Richter	0.449			2.019*	2.801*
CMC 1:1	0.157				4.821*
Yu´v´	0.733				

N = 80 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.573	0.456	0.126	0.819
L*u*v*	-0.026	2.918*	2.228*	0.658	5.073*
L*a*b*	0.573		0.690	2.260*	2.155*
Richter	0.456			1.570	2.845*
CMC 1:1	0.126				4.415*
Yu´v´	0.819				

N = 40 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.705	0.548	0.250	0.762
L*u*v*	0.012	3.723*	2.596*	1.045	4.258*
L*a*b*	0.705		1.127	2.678*	0.536
Richter	0.548			1.551	1.662
CMC 1:1	0.250				3.213*
Yu´v´	0.762				

N = 40 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.026	0.164	0.012
L*a*b*	0.573	0.969	0.705
Richter	0.456	0.533	0.548
CMC 1:1	0.126	0.551	0.250
Yu´v´	0.819	0.650	0.762

N = 40 * z´ score significant at $p \leq 0.05$

Table E-13. Correlations of Perceived Color Differences Means with Calculated Color Differences: Global Normalization Approach - Red

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.571	0.449	0.157	0.733
L*u*v*	-0.011	4.094*	3.073*	1.053	5.874*
L*a*b*	0.571		1.021	3.040*	1.781
Richter	0.449			2.019*	2.801*
CMC 1:1	0.157				4.821*
Yu´v´	0.733				

N = 80 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.573	0.456	0.126	0.819
L*u*v*	-0.026	2.918*	2.228*	0.658	5.073*
L*a*b*	0.573		0.690	2.260*	2.155*
Richter	0.456			1.570	2.845*
CMC 1:1	0.126				4.415*
Yu´v´	0.819				

N = 40 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.705	0.548	0.250	0.762
L*u*v*	0.012	3.723*	2.596*	1.045	4.258*
L*a*b*	0.705		1.127	2.678*	0.536
Richter	0.548			1.551	1.662
CMC 1:1	0.250				3.213*
Yu´v´	0.762				

N = 40 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.026	0.164	0.012
L*a*b*	0.573	0.969	0.705
Richter	0.456	0.533	0.548
CMC 1:1	0.126	0.551	0.250
Yu´v´	0.819	0.650	0.762

N = 40 * z´ score significant at $p \leq 0.05$

Table E-14 Correlations of Perceived Color Differences Means with Calculated Color Differences: Global Normalization Approach - Blue

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.660	0.289	0.444	0.566
L*u*v*	0.507	1.449	1.620	0.509	0.517
L*a*b*	0.660		3.069*	1.958	0.932
Richter	0.289			1.111	2.137*
CMC 1:1	0.444				1.026
Yu´v´	0.566				

N = 80 * z´ score significant at p ≤ 0.05

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.668	0.293	0.518	0.595
L*u*v*	0.579	0.626	1.545	0.376	0.105
L*a*b*	0.668		2.171*	1.002	0.521
Richter	0.293			1.169	1.651
CMC 1:1	0.518				0.482
Yu´v´	0.595				

N = 40 * z´ score significant at p ≤ 0.05

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.760	0.333	0.398	0.617
L*u*v*	0.476	2.061*	0.738	0.416	0.869
L*a*b*	0.760		2.799*	2.477*	1.193
Richter	0.333			0.322	1.607
CMC 1:1	0.398				1.284
Yu´v´	0.617				

N = 40 * z´ score significant at p ≤ 0.05

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.579	0.614	0.476
L*a*b*	0.668	0.821	0.760
Richter	0.293	0.193	0.333
CMC 1:1	0.518	0.654	0.398
Yu´v´	0.595	0.149	0.617

N = 40 * z´ score significant at p ≤ 0.05

Table E-15. Correlations of Perceived Color Differences Means with Calculated Color Differences: Global Normalization Approach - Yellow

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.578	0.681	0.336	0.699
L*u*v*	-0.171	5.157*	6.228*	3.236*	6.442*
L*a*b*	0.578		1.071	1.921	1.285
Richter	0.681			2.992*	0.214
CMC 1:1	0.336				3.206*
Yu´v´	0.699				

N = 80 * z´ score significant at p ≤ 0.05

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.651	0.742	0.373	0.780
L*u*v*	-0.214	4.279*	5.043*	2.621*	5.431*
L*a*b*	0.651		0.765	1.658	1.153
Richter	0.742			2.423*	0.388
CMC 1:1	0.373				2.810*
Yu´v´	0.780				

N = 40 * z´ score significant at p ≤ 0.05

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.635	0.788	0.378	0.781
L*u*v*	-0.154	3.894*	5.256*	2.378*	5.182*
L*a*b*	0.635		1.362	1.516	1.288
Richter	0.788			2.879*	0.074
CMC 1:1	0.378				2.804*
Yu´v´	0.781				

N = 40 * z´ score significant at p ≤ 0.05

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.214	0.265	-0.154
L*a*b*	0.651	0.119	0.635
Richter	0.742	0.478	0.788
CMC 1:1	0.373	0.023	0.378
Yu´v´	0.780	0.017	0.781

N = 40 * z´ score significant at p ≤ 0.05

Table E-16. Correlations of Perceived Color Differences Means with Calculated Color Differences: Global Normalization Approach - Neutral

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.684	0.547	0.202	0.198
L*u*v*	0.635	0.540	0.840	3.376*	3.403*
L*a*b*	0.684		1.380	3.916*	3.943*
Richter	0.547			2.535*	2.563*
CMC 1:1	0.202				0.027
Yu´v´	0.198				

N = 80 * z´ score significant at p ≤ 0.05

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.691	0.519	0.228	0.226
L*u*v*	0.626	0.488	0.688	2.167*	2.177*
L*a*b*	0.691		1.176	2.655*	2.665*
Richter	0.519			1.479	1.489
CMC 1:1	0.228				0.009
Yu´v´	0.226				

N = 40 * z´ score significant at p ≤ 0.05

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.802	0.688	0.204	0.196
L*u*v*	0.765	0.415	0.707	3.446*	3.482*
L*a*b*	0.802		1.122	3.861*	3.897*
Richter	0.688			2.739*	2.775*
CMC 1:1	0.204				0.036
Yu´v´	0.196				

N = 40 * z´ score significant at p ≤ 0.05

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.626	1.174	0.765
L*a*b*	0.691	1.101	0.802
Richter	0.519	1.155	0.688
CMC 1:1	0.228	0.104	0.204
Yu´v´	0.226	0.131	0.196

N = 40 * z´ score significant at p ≤ 0.05

Table E-17. Correlations of Perceived Color Differences Means with Calculated Color Differences: Global Normalization Approach - Cyan

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.645	0.363	0.177	0.665
L*u*v*	0.061	4.378*	1.983*	0.734	4.598*
L*a*b*	0.645		2.396*	3.644*	0.220
Richter	0.363			1.249	2.615*
CMC 1:1	0.177				3.864*
Yu´v´	0.665				

N = 80 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.636	0.343	0.183	0.683
L*u*v*	0.100	2.801*	1.107	0.366	3.160*
L*a*b*	0.636		1.694	2.435*	0.360
Richter	0.343			0.741	2.054*
CMC 1:1	0.183				2.795*
Yu´v´	0.683				

N = 40 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.750	0.446	0.193	0.731
L*u*v*	0.009	4.145*	2.024*	0.805	3.964*
L*a*b*	0.750		2.121*	3.340*	0.181
Richter	0.446			1.219	1.940
CMC 1:1	0.193				3.160*
Yu´v´	0.731				

N = 40 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.100	0.395	0.009
L*a*b*	0.636	0.949	0.750
Richter	0.343	0.522	0.446
CMC 1:1	0.183	0.044	0.193
Yu´v´	0.683	0.408	0.731

N = 40 * z´ score significant at $p \leq 0.05$

Table E-18. Correlations of Perceived Color Differences Means with Calculated Color Differences: Global Normalization Approach - Caucasian

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.751	0.559	0.507	0.350
L*u*v*	0.237	4.559*	2.418*	1.968*	0.774
L*a*b*	0.751		2.140*	2.590*	3.785*
Richter	0.559			0.450	1.645
CMC 1:1	0.507				1.195
Yu´v´	0.350				

N = 80 * z´ score significant at p ≤ 0.05

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.847	0.632	0.602	0.377
L*u*v*	0.306	4.006*	1.848	1.638	0.349
L*a*b*	0.847		2.158*	2.368*	3.657*
Richter	0.632			0.210	1.499
CMC 1:1	0.602				1.289
Yu´v´	0.377				

N = 40 * z´ score significant at p ≤ 0.05

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.844	0.625	0.523	0.422
L*u*v*	0.207	4.413*	2.250*	1.593	1.034
L*a*b*	0.844		2.164*	2.820*	3.380*
Richter	0.625			0.656	1.216
CMC 1:1	0.523				0.560
Yu´v´	0.422				

N = 40 * z´ score significant at p ≤ 0.05

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.306	0.455	0.207
L*a*b*	0.847	0.048	0.844
Richter	0.632	0.053	0.625
CMC 1:1	0.602	0.500	0.523
Yu´v´	0.377	0.230	0.422

N = 40 * z´ score significant at p ≤ 0.05

Local Normalization Approach

Table E-19. Correlations of Perceived Color Differences with Calculated Color Differences: Local Normalization Approach - All Color Regions

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.319	0.193	0.150	0.141
L*u*v*	-0.059	22.027*	14.358*	11.848*	11.368*
L*a*b*	0.319		7.668*	10.179*	10.659*
Richter	0.193			2.510*	2.991*
CMC 1:1	0.150				0.480
Yu´v´	0.141				

N = 6400 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.286	0.165	0.149	0.129
L*u*v*	-0.056	13.976*	8.894*	8.227*	7.417*
L*a*b*	0.286		5.082*	5.749*	6.559*
Richter	0.165			0.667	1.477
CMC 1:1	0.149				0.810
Yu´v´	0.129				

N = 3200 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.536	0.343	0.212	0.231
L*u*v*	-0.089	27.511*	17.876*	12.201*	12.985*
L*a*b*	0.536		9.635*	15.310*	14.526*
Richter	0.343			5.674*	4.891*
CMC 1:1	0.212				0.783
Yu´v´	0.231				

N = 3200 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.056	1.355	-0.089
L*a*b*	0.286	12.179*	0.536
Richter	0.165	7.626*	0.343
CMC 1:1	0.149	2.619*	0.212
Yu´v´	0.129	4.212*	0.231

N = 3200 * z´ score significant at $p \leq 0.05$

Table E-20. Correlations of Perceived Color Differences with Calculated Color Differences: Local Normalization Approach - Magenta

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.333	0.127	0.099	0.397
L*u*v*	0.217	2.515*	1.849	2.410*	3.999*
L*a*b*	0.333		4.364*	4.925*	1.484
Richter	0.127			0.561	5.848*
CMC 1:1	0.099				6.409*
Yu´v´	0.397				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.271	0.074	0.082	0.360
L*u*v*	0.170	1.501	1.368	1.260	2.901*
L*a*b*	0.271		2.869*	2.762*	1.400
Richter	0.074			0.107	4.269*
CMC 1:1	0.082				4.162*
Yu´v´	0.360				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.661	0.330	0.194	0.690
L*u*v*	0.448	4.396*	1.967*	4.018*	5.150*
L*a*b*	0.661		6.363*	8.414*	0.754
Richter	0.330			2.050*	7.118*
CMC 1:1	0.194				9.168*
Yu´v´	0.690				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.170	4.375*	0.448
L*a*b*	0.271	7.279*	0.661
Richter	0.074	3.786*	0.330
CMC 1:1	0.082	1.610	0.194
Yu´v´	0.360	6.637*	0.690

N = 400 * z´ score significant at $p \leq 0.05$

Table E-21. Correlations of Perceived Color Differences with Calculated Color Differences: Local Normalization Approach - Green

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.325	0.256	0.090	0.418
L*u*v*	-0.006	6.868*	5.357*	1.924	9.013*
L*a*b*	0.325		1.510	4.944*	2.146*
Richter	0.256			3.434*	3.656*
CMC 1:1	0.090				7.090*
Yu´v´	0.418				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.369	0.293	0.081	0.527
L*u*v*	-0.017	5.691*	4.491*	1.384	8.490*
L*a*b*	0.369		1.200	4.307*	2.799*
Richter	0.293			3.107*	3.999*
CMC 1:1	0.081				7.106*
Yu´v´	0.527				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.289	0.224	0.102	0.312
L*u*v*	0.005	4.121*	3.147*	1.378	4.481*
L*a*b*	0.289		0.973	2.743*	0.361
Richter	0.224			1.769	1.334
CMC 1:1	0.102				3.103*
Yu´v´	0.312				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.017	0.306	0.005
L*a*b*	0.369	1.265	0.289
Richter	0.293	1.038	0.224
CMC 1:1	0.081	0.300	0.102
Yu´v´	0.527	3.703*	0.312
	N = 400	* z´ score significant at $p \leq 0.05$	

Table E-22. Correlations of Perceived Color Differences with Calculated Color Differences: Local Normalization Approach - Red

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.550	0.330	0.235	0.433
L*u*v*	-0.084	14.009*	8.518*	6.446*	10.920*
L*a*b*	0.550		5.491*	7.563*	3.089*
Richter	0.330			2.072*	2.401*
CMC 1:1	0.235				4.474*
Yu´v´	0.433				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.530	0.313	0.256	0.394
L*u*v*	-0.106	9.822*	6.068*	5.189*	7.368*
L*a*b*	0.530		3.754*	4.633*	2.454*
Richter	0.313			0.880	1.300
CMC 1:1	0.256				2.179*
Yu´v´	0.394				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.717	0.441	0.245	0.613
L*u*v*	-0.057	13.499*	7.472*	4.326*	10.847*
L*a*b*	0.717		6.027*	9.172*	2.651*
Richter	0.441			3.145*	3.376*
CMC 1:1	0.245				6.521*
Yu´v´	0.613				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	**z´ score**	**Expert**
L*u*v*	-0.106	0.699	-0.057
L*a*b*	0.530	4.376*	0.717
Richter	0.313	2.103*	0.441
CMC 1:1	0.256	0.163	0.245
Yu´v´	0.394	4.179*	0.613
	N = 400	* z´ score significant at $p \leq 0.05$	

Table E-23. Correlations of Perceived Color Differences with Calculated Color Differences: Local Normalization Approach - Blue

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.425	0.186	0.286	0.365
L*u*v*	0.327	2.289*	3.012*	0.903	0.869
L*a*b*	0.425		5.301*	3.193*	1.421
Richter	0.186			2.108*	3.880*
CMC 1:1	0.286				1.772
Yu´v´	0.365				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.389	0.170	0.302	0.347
L*u*v*	0.337	0.838	2.521*	0.559	0.150
L*a*b*	0.389		3.359*	1.397	0.688
Richter	0.170			1.962*	2.671*
CMC 1:1	0.302				0.709
Yu´v´	0.347				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.664	0.291	0.347	0.539
L*u*v*	0.416	5.030*	2.018*	1.131	2.253*
L*a*b*	0.664		7.048*	6.161*	2.777*
Richter	0.291			0.887	4.271*
CMC 1:1	0.347				3.384*
Yu´v´	0.539				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.337	1.289	0.416
L*a*b*	0.389	5.481*	0.664
Richter	0.170	1.792	0.291
CMC 1:1	0.302	0.717	0.347
Yu´v´	0.347	3.392*	0.539

N = 400 * z´ score significant at $p \leq 0.05$

Table E-24. Correlations of Perceived Color Differences with Calculated Color Differences: Local Normalization Approach - Yellow

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.423	0.499	0.246	0.512
L*u*v*	-0.125	11.521*	13.450*	7.522*	13.802*
L*a*b*	0.423		1.928	3.999*	2.281*
Richter	0.499			5.927*	0.352
CMC 1:1	0.246				6.280*
Yu´v´	0.512				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.423	0.482	0.242	0.507
L*u*v*	-0.139	8.332*	9.379*	5.455*	9.836*
L*a*b*	0.423		1.047	2.877*	1.504
Richter	0.482			3.924*	0.457
CMC 1:1	0.242				4.382*
Yu´v´	0.507				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.564	0.700	0.336	0.694
L*u*v*	-0.138	10.956*	14.184*	6.872*	14.020*
L*a*b*	0.564		3.228*	4.084*	3.064*
Richter	0.700			7.312*	0.164
CMC 1:1	0.336				7.148*
Yu´v´	0.694				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.139	0.017	-0.138
L*a*b*	0.423	2.640*	0.564
Richter	0.482	4.821*	0.700
CMC 1:1	0.242	1.434	0.336
Yu´v´	0.507	4.200*	0.694

N = 400 * z´ score significant at $p \leq 0.05$

Table E-25. Correlations of Perceived Color Differences with Calculated Color Differences: Local Normalization Approach - Neutral

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.147	0.117	0.043	0.043
L*u*v*	0.136	0.215	0.382	1.868	1.884
L*a*b*	0.147		0.597	2.083*	2.099*
Richter	0.117			1.485	1.502
CMC 1:1	0.043				0.017
Yu´v´	0.043				

N = 800 * z´ score significant at p ≤ 0.05

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.115	0.087	0.038	0.038
L*u*v*	0.105	0.153	0.254	0.944	0.948
L*a*b*	0.115		0.407	1.097	1.101
Richter	0.087			0.690	0.694
CMC 1:1	0.038				0.004
Yu´v´	0.038				

N = 400 * z´ score significant at p ≤ 0.05

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.688	0.590	0.175	0.169
L*u*v*	0.656	0.822	1.529	8.586*	8.682*
L*a*b*	0.688		2.350*	9.408*	9.504*
Richter	0.590			7.058*	7.154*
CMC 1:1	0.175				0.096
Yu´v´	0.169				

N = 400 * z´ score significant at p ≤ 0.05

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.105	9.600*	0.656
L*a*b*	0.115	10.268*	0.688
Richter	0.087	8.325*	0.590
CMC 1:1	0.038	1.958	0.175
Yu´v´	0.038	1.866	0.169

N = 400 * z´ score significant at p ≤ 0.05

Table E-26. Correlations of Perceived Color Differences with Calculated Color Differences: Local Normalization Approach - Cyan

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.434	0.243	0.106	0.455
L*u*v*	0.046	8.356*	4.024*	1.212	8.885*
L*a*b*	0.434		4.332*	7.143*	0.529
Richter	0.243			2.812*	4.861*
CMC 1:1	0.106				7.673*
Yu´v´	0.455				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.392	0.212	0.113	0.421
L*u*v*	0.062	4.964*	2.155*	0.722	5.455*
L*a*b*	0.392		2.809*	4.242*	0.491
Richter	0.212			1.433	3.300*
CMC 1:1	0.113				4.733*
Yu´v´	0.421				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.639	0.374	0.120	0.649
L*u*v*	0.023	10.332*	5.215*	1.375	10.568*
L*a*b*	0.639		5.117*	8.957*	0.235
Richter	0.374			3.840*	5.353*
CMC 1:1	0.120				9.192*
Yu´v´	0.649				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.062	0.546	0.023
L*a*b*	0.392	4.822*	0.639
Richter	0.212	2.513*	0.374
CMC 1:1	0.113	0.107	0.120
Yu´v´	0.421	4.566*	0.649

N = 400 * z´ score significant at $p \leq 0.05$

Table E-27. Correlations of Perceived Color Differences with Calculated Color Differences: Local Normalization Approach - Caucasian

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.485	0.374	0.318	0.223
L*u*v*	0.133	7.889*	5.160*	3.892*	1.858
L*a*b*	0.485		2.730*	3.998*	6.031*
Richter	0.374			1.268	3.302*
CMC 1:1	0.318				2.034*
Yu´v´	0.223				

N = 800 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.479	0.358	0.341	0.213
L*u*v*	0.173	4.896*	2.814*	2.538*	0.592
L*a*b*	0.479		2.082*	2.358*	4.304*
Richter	0.358			0.276	2.221*
CMC 1:1	0.341				1.946
Yu´v´	0.213				

N = 400 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.692	0.560	0.392	0.336
L*u*v*	0.095	10.666*	7.584*	4.492*	3.594*
L*a*b*	0.692		3.082*	6.174*	7.072*
Richter	0.560			3.092*	3.990*
CMC 1:1	0.392				0.898
Yu´v´	0.336				

N = 400 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.173	1.123	0.095
L*a*b*	0.479	4.647*	0.692
Richter	0.358	3.648*	0.560
CMC 1:1	0.341	0.831	0.392
Yu´v´	0.213	1.879	0.336

N = 400 * z´ score significant at $p \leq 0.05$

Local Normalization Approach - Mean Values

Table E-28. Correlations of Perceived Color Differences Means with Calculated Color Differences: Local Normalization Approach - All Colors

All Subjects

	r	L*a*b* 0.640	Richter 0.366	CMC 1:1 0.289	Yu´v´ 0.268
L*u*v*	-0.112	15.528*	8.863*	7.324*	6.913*
L*a*b*	0.640		6.665*	8.205*	8.615*
Richter	0.366			1.540	1.950
CMC 1:1	0.289				0.410
Yu´v´	0.268				

N = 640 * z´ score significant at $p \leq 0.05$

Novice Subjects

	r	L*a*b* 0.647	Richter 0.338	CMC 1:1 0.320	Yu´v´ 0.266
L*u*v*	-0.117	11.186*	5.916*	5.660*	4.913*
L*a*b*	0.647		5.270*	5.526*	6.273*
Richter	0.338			0.256	1.003
CMC 1:1	0.320				0.747
Yu´v´	0.266				

N = 320 * z´ score significant at $p \leq 0.05$

Expert Subjects

	r	L*a*b* 0.734	Richter 0.470	CMC 1:1 0.291	Yu´v´ 0.316
L*u*v*	-0.123	13.353*	7.969*	5.319*	5.672*
L*a*b*	0.734		5.385*	8.035*	7.682*
Richter	0.470			2.650*	2.297*
CMC 1:1	0.291				0.353
Yu´v´	0.316				

N = 320 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.117	0.077	-0.123
L*a*b*	0.647	2.105*	0.734
Richter	0.338	1.992*	0.470
CMC 1:1	0.320	0.403	0.291
Yu´v´	0.266	0.688	0.316

N = 320 * z´ score significant at $p \leq 0.05$

Table E-29 Correlations of Perceived Color Differences Means with Calculated Color Differences: Local Normalization Approach - Magenta

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.531	0.202	0.158	0.633
L*u*v*	0.345	1.438	0.961	1.244	2.399*
L*a*b*	0.531		2.400*	2.682*	0.961
Richter	0.202			0.282	3.360*
CMC 1:1	0.158				3.643*
Yu´v´	0.633				

N = 80 * z´ score significant at p ≤ 0.05

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.495	0.135	0.149	0.659
L*u*v*	0.310	0.955	0.794	0.733	2.024*
L*a*b*	0.495		1.750	1.688	1.068
Richter	0.135			0.061	2.818*
CMC 1:1	0.149				2.757*
Yu´v´	0.659				

N = 40 * z´ score significant at p ≤ 0.05

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.762	0.380	0.224	0.795
L*u*v*	0.517	1.844	0.741	1.481	2.205*
L*a*b*	0.762		2.585*	3.325*	0.361
Richter	0.380			0.741	2.946*
CMC 1:1	0.224				3.686*
Yu´v´	0.795				

N = 40 * z´ score significant at p ≤ 0.05

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.310	1.080	0.517
L*a*b*	0.495	1.968*	0.762
Richter	0.135	1.136	0.380
CMC 1:1	0.149	0.335	0.224
Yu´v´	0.659	1.265	0.795

N = 40 * z´ score significant at p ≤ 0.05

Table E-30. Correlations of Perceived Color Differences Means with Calculated Color Differences: Local Normalization Approach - Green

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.571	0.449	0.157	0.733
L*u*v*	-0.011	4.093*	3.073*	1.054	5.874*
L*a*b*	0.571		1.021	3.039*	1.781
Richter	0.449			2.019*	2.801*
CMC 1:1	0.157				4.820*
Yu´v´	0.733				

N = 80 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.573	0.456	0.126	0.819
L*u*v*	-0.026	2.918*	2.228*	0.658	5.073*
L*a*b*	0.573		0.690	2.260*	2.155*
Richter	0.456			1.570	2.845*
CMC 1:1	0.126				4.415*
Yu´v´	0.819				

N = 40 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.705	0.548	0.250	0.762
L*u*v*	0.012	3.723*	2.597*	1.046	4.260*
L*a*b*	0.705		1.126	2.677*	0.537
Richter	0.548			1.550	1.663
CMC 1:1	0.250				3.214*
Yu´v´	0.762				

N = 40 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.026	0.163	0.012
L*a*b*	0.573	0.968	0.705
Richter	0.456	0.532	0.548
CMC 1:1	0.126	0.551	0.250
Yu´v´	0.819	0.650	0.762

N = 40 * z´ score significant at $p \leq 0.05$

Table E-31. Correlations of Perceived Color Differences Means with Calculated Color Differences: Local Normalization Approach - Red

All Subjects

	r	L*a*b* 0.787	Richter 0.472	CMC 1:1 0.336	Yu´v´ 0.619
L*u*v*	-0.120	7.340*	3.932*	2.914*	5.237*
L*a*b*	0.787		3.408*	4.426*	2.103*
Richter	0.472			1.018	1.305
CMC 1:1	0.336				2.323*
Yu´v´	0.619				

N = 80 * z´ score significant at $p \leq 0.05$

Novice Subjects

	r	L*a*b* 0.834	Richter 0.493	CMC 1:1 0.403	Yu´v´ 0.620
L*u*v*	-0.167	5.897*	3.049*	2.561*	3.843*
L*a*b*	0.834		2.848*	3.336*	2.054*
Richter	0.493			0.488	0.794
CMC 1:1	0.403				1.282
Yu´v´	0.620				

N = 40 * z´ score significant at $p \leq 0.05$

Expert Subjects

	r	L*a*b* 0.825	Richter 0.508	CMC 1:1 0.282	Yu´v´ 0.705
L*u*v*	-0.066	5.326*	2.690*	1.529	4.054*
L*a*b*	0.825		2.636*	3.797*	1.272
Richter	0.508			1.161	1.364
CMC 1:1	0.282				2.525*
Yu´v´	0.705				

N = 40 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.167	0.444	-0.066
L*a*b*	0.834	0.127	0.825
Richter	0.493	0.085	0.508
CMC 1:1	0.403	0.589	0.282
Yu´v´	0.620	0.655	0.705

N = 40 * z´ score significant at $p \leq 0.05$

Table E-32. Correlations of Perceived Color Differences Means with Calculated Color Differences: Local Normalization Approach - Blue

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.659	0.289	0.443	0.567
L*u*v*	0.507	1.446	1.622	0.511	0.518
L*a*b*	0.659		3.068*	1.957	0.928
Richter	0.289			1.111	2.140*
CMC 1:1	0.443				1.029
Yu´v´	0.567				

N = 80 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.667	0.293	0.518	0.595
L*u*v*	0.579	0.625	1.546	0.376	0.105
L*a*b*	0.667		2.171*	1.001	0.519
Richter	0.293			1.170	1.651
CMC 1:1	0.518				0.481
Yu´v´	0.595				

N = 40 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.760	0.333	0.397	0.618
L*u*v*	0.476	2.059*	0.741	0.420	0.872
L*a*b*	0.760		2.800*	2.479*	1.187
Richter	0.333			0.321	1.613
CMC 1:1	0.397				1.292
Yu´v´	0.618				

N = 40 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.579	0.613	0.476
L*a*b*	0.667	0.821	0.760
Richter	0.293	0.192	0.333
CMC 1:1	0.518	0.657	0.397
Yu´v´	0.595	0.153	0.618

N = 40 * z´ score significant at $p \leq 0.05$

Table E-33. Correlations of Perceived Color Differences Means with Calculated Color Differences: Local Normalization Approach - Yellow

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.638	0.593	0.489	0.490
L*u*v*	-0.016	4.789*	4.337*	3.422*	3.424*
L*a*b*	0.638		0.452	1.368	1.366
Richter	0.593			0.915	0.914
CMC 1:1	0.489				0.002
Yu´v´	0.490				

N = 80 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.650	0.414	0.603	0.216
L*u*v*	-0.173	4.091*	2.648*	3.757*	1.696
L*a*b*	0.650		1.443	0.334	2.395*
Richter	0.414			1.109	0.952
CMC 1:1	0.603				2.061*
Yu´v´	0.216				

N = 40 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.635	0.788	0.378	0.781
L*u*v*	-0.154	3.894*	5.256*	2.378*	5.182*
L*a*b*	0.635		1.362	1.516	1.288
Richter	0.788			2.879*	0.074
CMC 1:1	0.378				2.804*
Yu´v´	0.781				

N = 40 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	-0.173	0.084	-0.154
L*a*b*	0.650	0.112	0.635
Richter	0.414	2.692*	0.788
CMC 1:1	0.603	1.295	0.378
Yu´v´	0.216	3.571*	0.781
	N = 40	* z´ score significant at $p \leq 0.05$	

Table E-34. Correlations of Perceived Color Differences Means with Calculated Color Differences: Local Normalization Approach - Neutral

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.684	0.547	0.202	0.198
L*u*v*	0.635	0.540	0.842	3.379*	3.402*
L*a*b*	0.684		1.382	3.919*	3.942*
Richter	0.547			2.537*	2.560*
CMC 1:1	0.202				0.024
Yu´v´	0.198				

N = 80 * z´ score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.691	0.519	0.227	0.226
L*u*v*	0.627	0.487	0.691	2.172*	2.177*
L*a*b*	0.691		1.178	2.660*	2.664*
Richter	0.519			1.481	1.486
CMC 1:1	0.227				0.005
Yu´v´	0.226				

N = 40 * z´ score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.803	0.688	0.204	0.196
L*u*v*	0.765	0.417	0.708	3.449*	3.485*
L*a*b*	0.803		1.125	3.866*	3.902*
Richter	0.688			2.741*	2.777*
CMC 1:1	0.204				0.036
Yu´v´	0.196				

N = 40 * z´ score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.627	1.175	0.765
L*a*b*	0.691	1.104	0.803
Richter	0.519	1.158	0.688
CMC 1:1	0.227	0.102	0.204
Yu´v´	0.226	0.133	0.196

N = 40 * z´ score significant at $p \leq 0.05$

Table E-35. Correlations of Perceived Color Differences Means with Calculated Color Differences: Local Normalization Approach - Cyan

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.640	0.358	0.157	0.672
L*u*v*	0.068	4.284*	1.904	0.562	4.625*
L*a*b*	0.640		2.381*	3.722*	0.341
Richter	0.358			1.342	2.722*
CMC 1:1	0.157				4.063*
Yu´v´	0.672				

N = 80 * z´ score significant at p ≤ 0.05

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.636	0.344	0.183	0.683
L*u*v*	0.100	2.799*	1.107	0.363	3.158*
L*a*b*	0.636		1.692	2.436*	0.359
Richter	0.344			0.744	2.051*
CMC 1:1	0.183				2.795*
Yu´v´	0.683				

N = 40 * z´ score significant at p ≤ 0.05

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu´v´
	r	0.738	0.432	0.139	0.749
L*u*v*	0.027	3.949*	1.872	0.488	4.056*
L*a*b*	0.738		2.077*	3.461*	0.107
Richter	0.432			1.385	2.183*
CMC 1:1	0.139				3.568*
Yu´v´	0.749				

N = 40 * z´ score significant at p ≤ 0.05

Novice vs. Expert Subjects

	Novice	z´ score	Expert
L*u*v*	0.100	0.318	0.027
L*a*b*	0.636	0.832	0.738
Richter	0.344	0.447	0.432
CMC 1:1	0.183	0.194	0.139
Yu´v´	0.683	0.580	0.749

N = 40 * z´ score significant at p ≤ 0.05

Table E-36. Correlations of Perceived Color Differences Means with Calculated Color Differences: Local Normalization Approach - Caucasian

All Subjects

		L*a*b*	Richter	CMC 1:1	Yu'v'
	r	0.739	0.570	0.484	0.341
L*u*v*	0.203	4.610*	2.737*	2.002*	0.923
L*a*b*	0.739		1.873	2.607*	3.687*
Richter	0.570			0.734	1.814
CMC 1:1	0.484				1.080
Yu'v'	0.341				

N = 80 * z' score significant at $p \leq 0.05$

Novice Subjects

		L*a*b*	Richter	CMC 1:1	Yu'v'
	r	0.848	0.633	0.602	0.377
L*u*v*	0.306	4.013*	1.852	1.639	0.349
L*a*b*	0.848		2.161*	2.374*	3.664*
Richter	0.633			0.213	1.502
CMC 1:1	0.602				1.290
Yu'v'	0.377				

N = 40 * z' score significant at $p \leq 0.05$

Expert Subjects

		L*a*b*	Richter	CMC 1:1	Yu'v'
	r	0.809	0.655	0.458	0.393
L*u*v*	0.110	4.355*	2.894*	1.651	1.310
L*a*b*	0.809		1.461	2.705*	3.046*
Richter	0.655			1.244	1.585
CMC 1:1	0.458				0.341
Yu'v'	0.393				

N = 40 * z' score significant at $p \leq 0.05$

Novice vs. Expert Subjects

	Novice	z' score	Expert
L*u*v*	0.306	0.881	0.110
L*a*b*	0.848	0.539	0.809
Richter	0.633	0.161	0.655
CMC 1:1	0.602	0.870	0.458
Yu'v'	0.377	0.079	0.393

N = 40 * z' score significant at $p \leq 0.05$

APPENDIX F - Perceived Color-Difference Plots

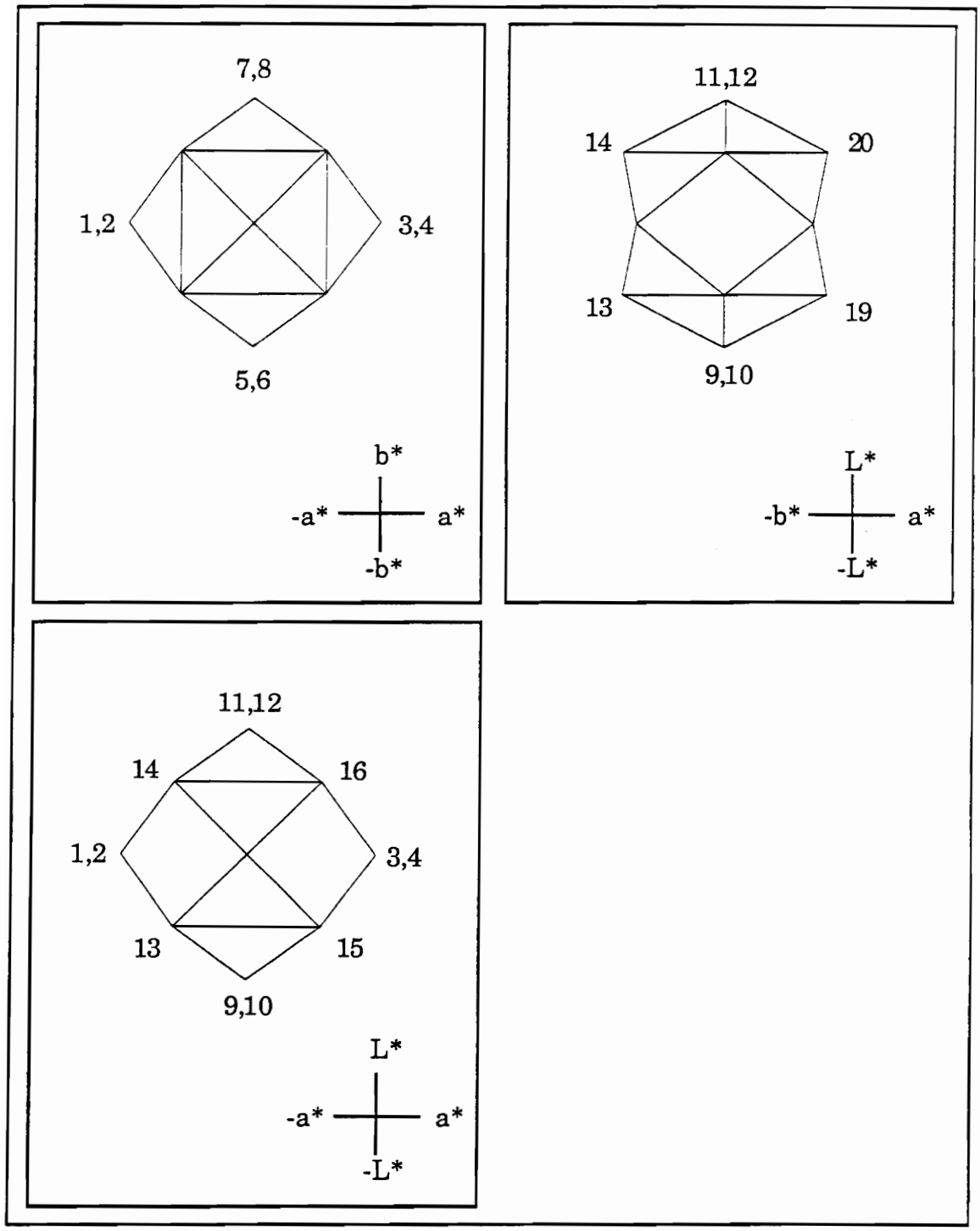

Figure F-1. Shape of an ideal perceived color-difference plot.

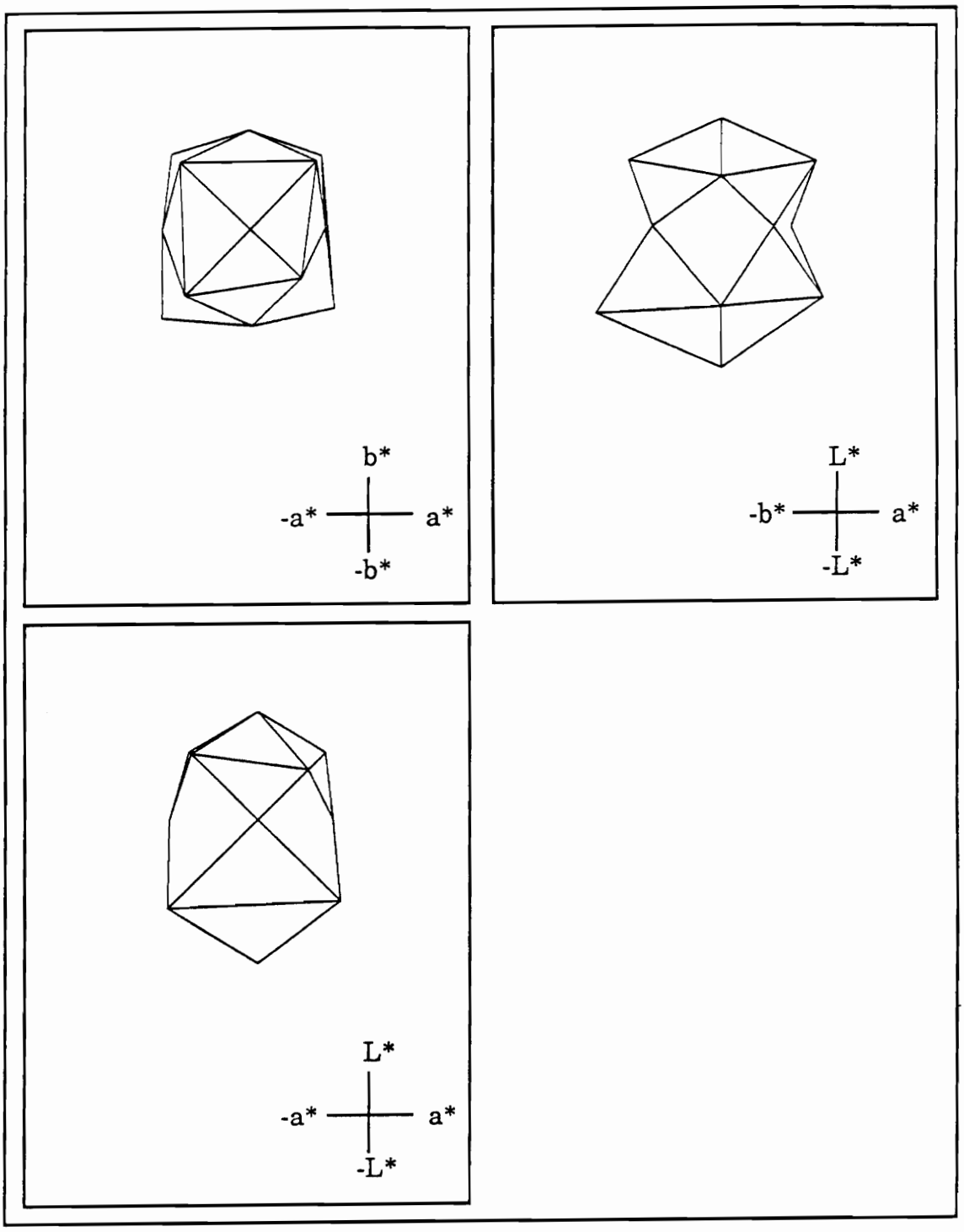

Figure F-2. Perceived color-difference plot: Magenta, 5ΔE, Novice.

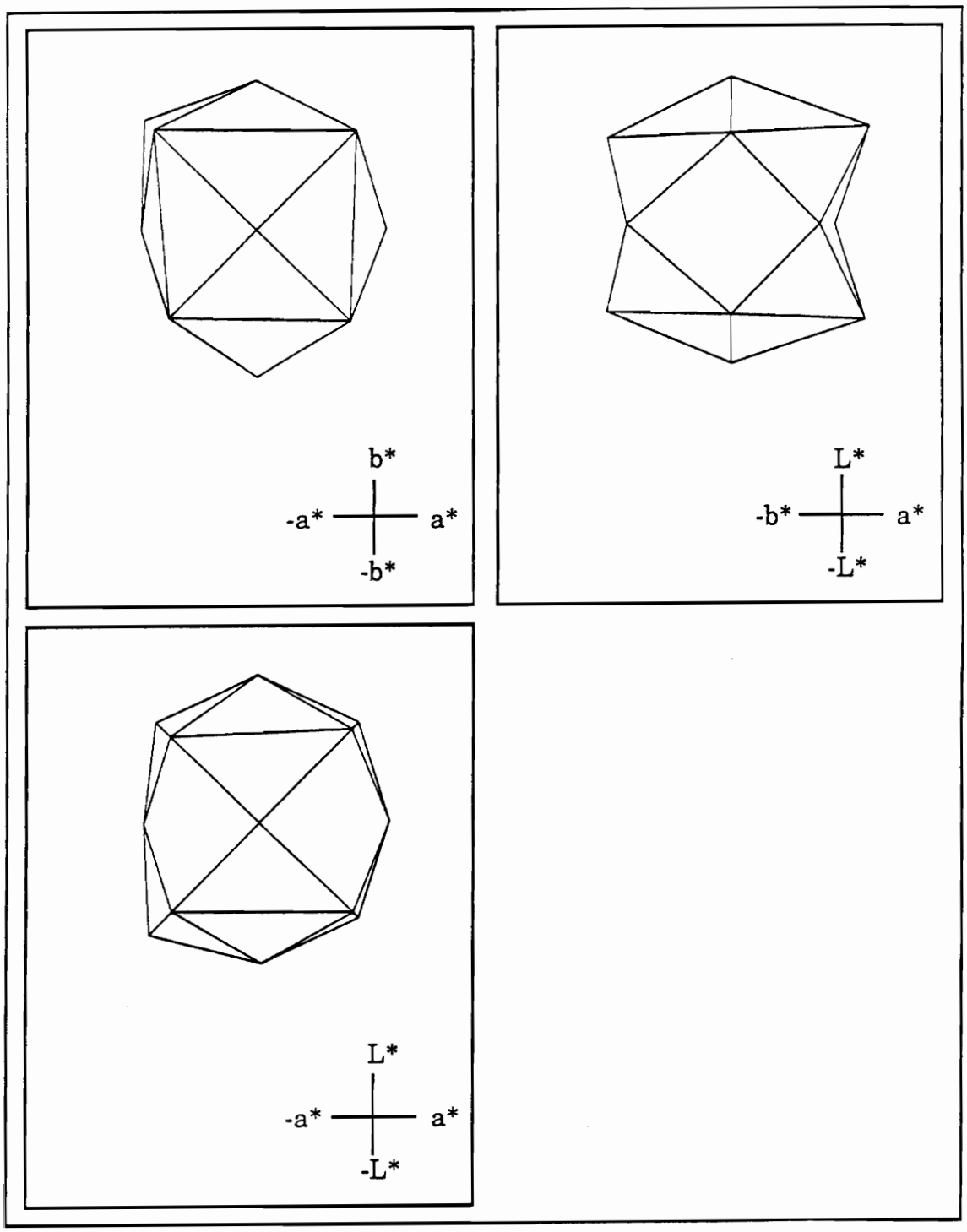

Figure F-3. Perceived color-difference plot: Magenta, 5ΔE, Expert.

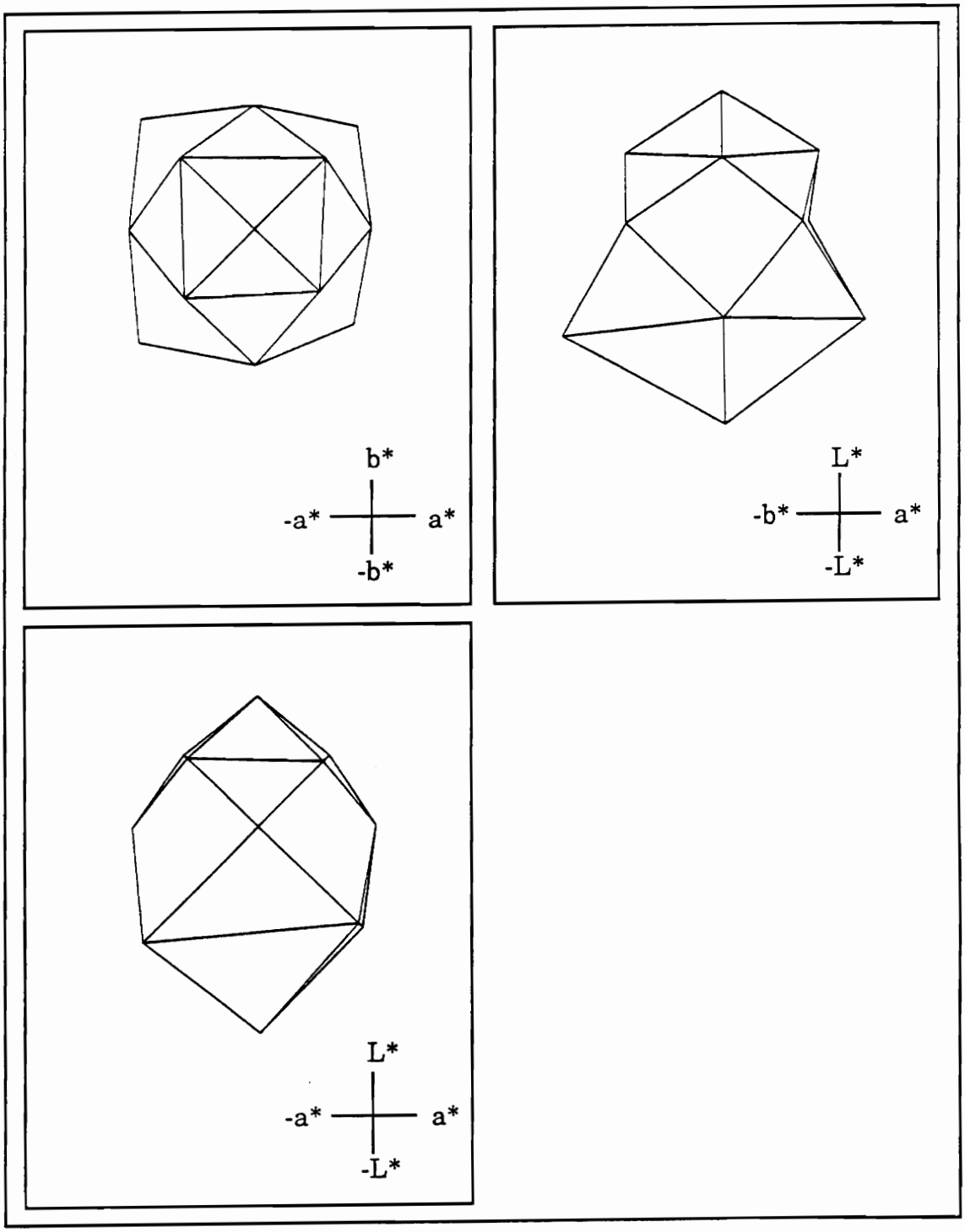

Figure F-4. Perceived color-difference plot: Magenta, 10ΔE, Novice.

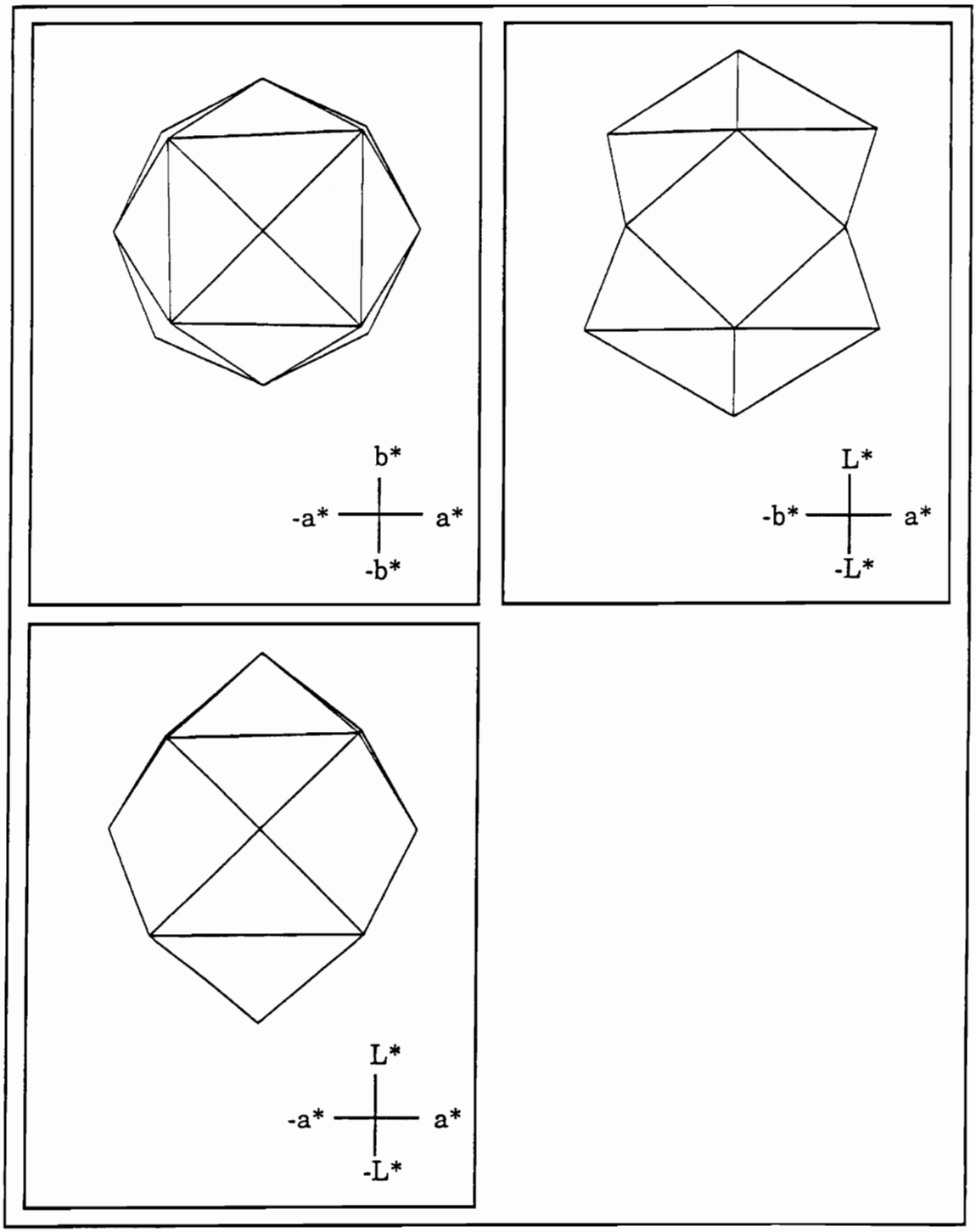

Figure F-5. Perceived color-difference plot: Magenta, 10ΔE, Expert.

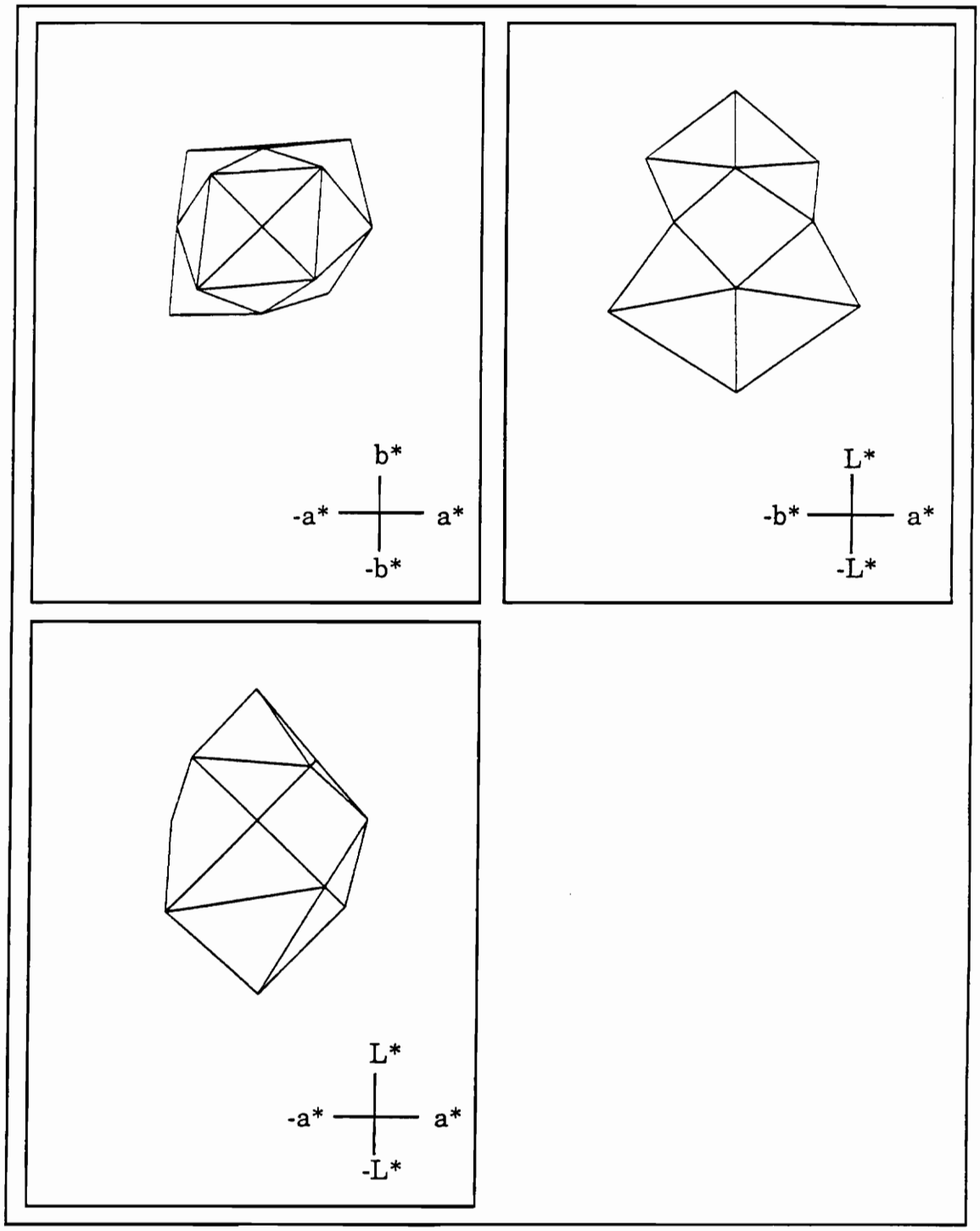

Figure F-6. Perceived color-difference plot: Green, 5ΔE, Novice.

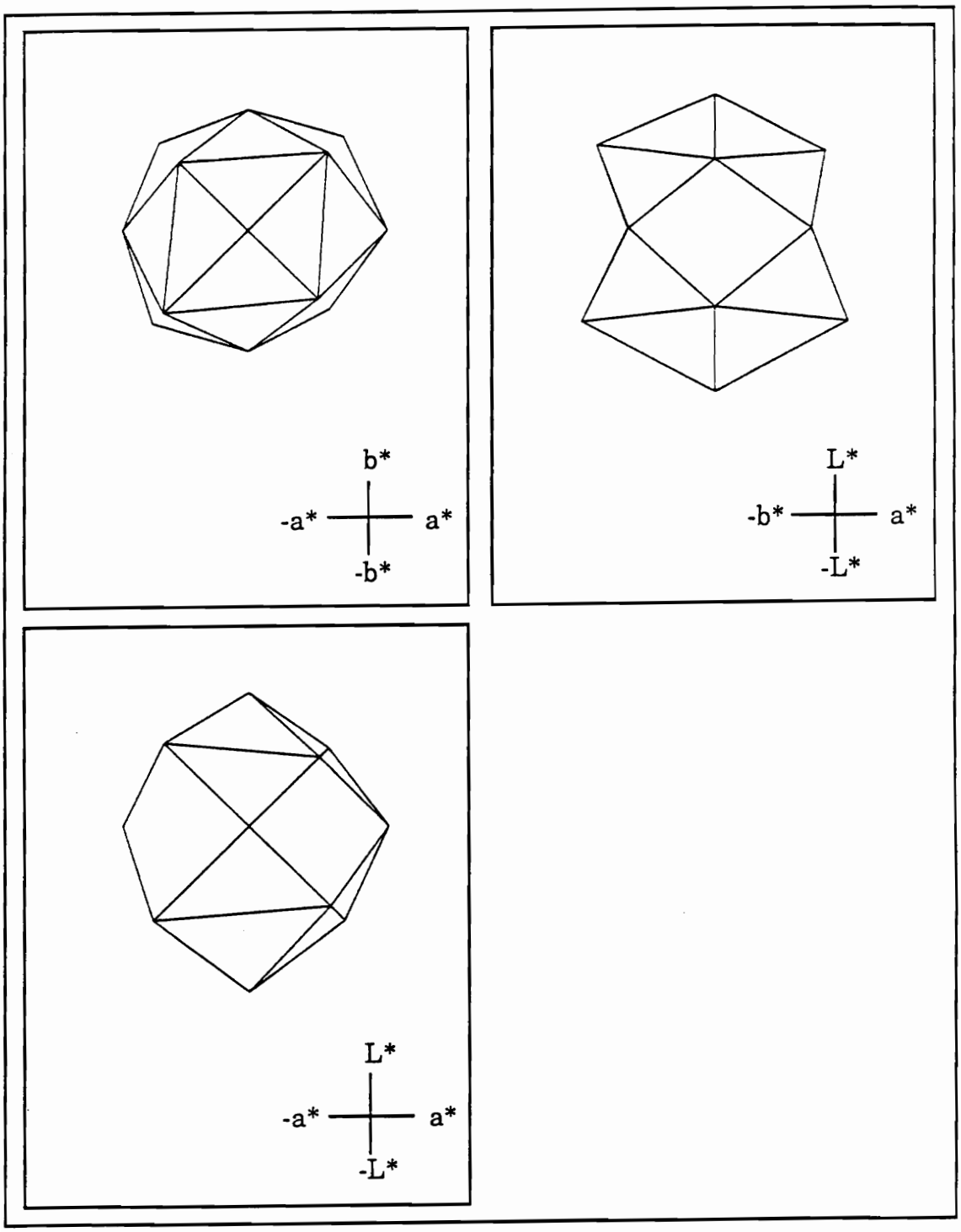

Figure F-7. Perceived color-difference plot: Green, 5ΔE, Expert.

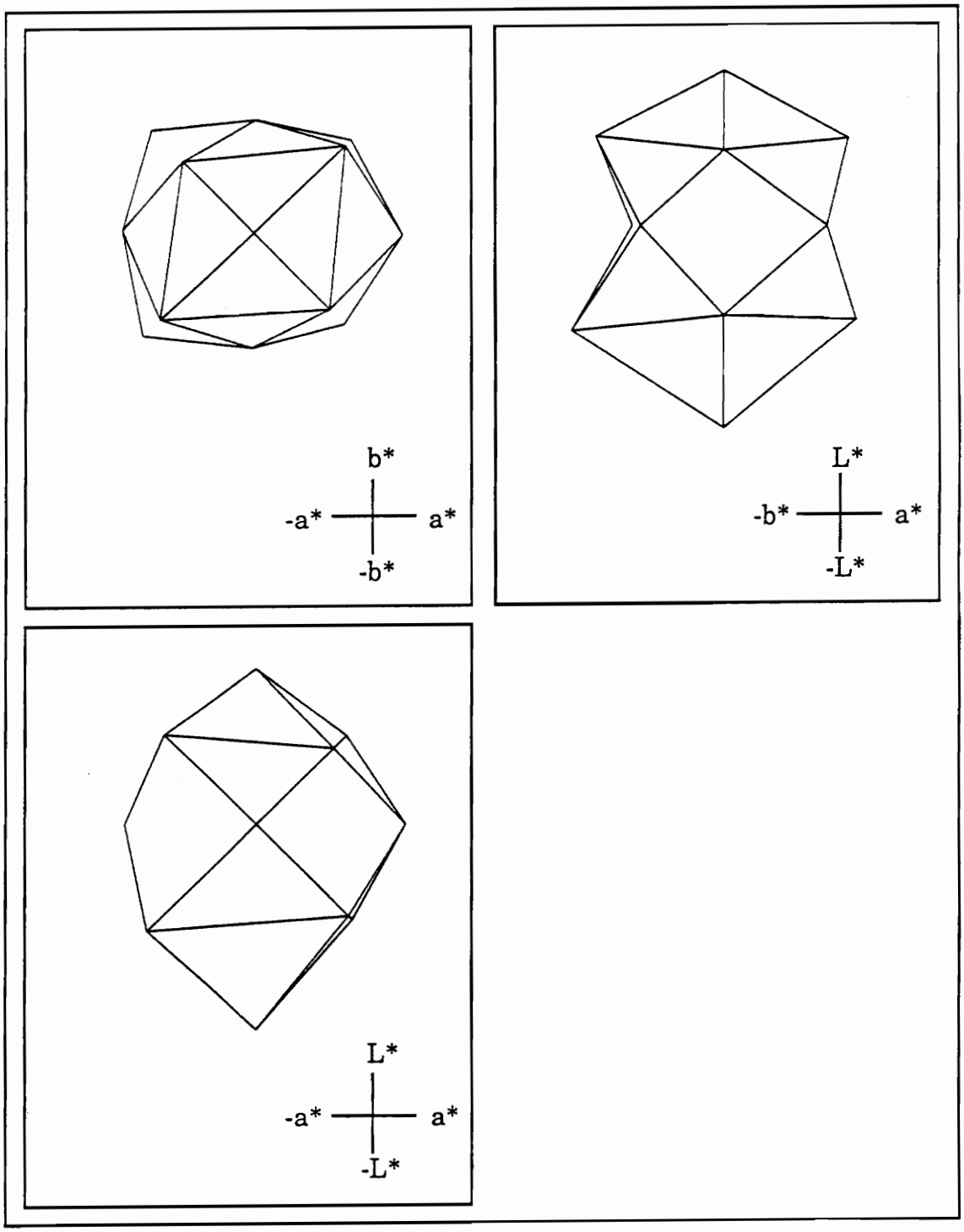

Figure F-8. Perceived color-difference plot: Green, 10ΔE, Novice.

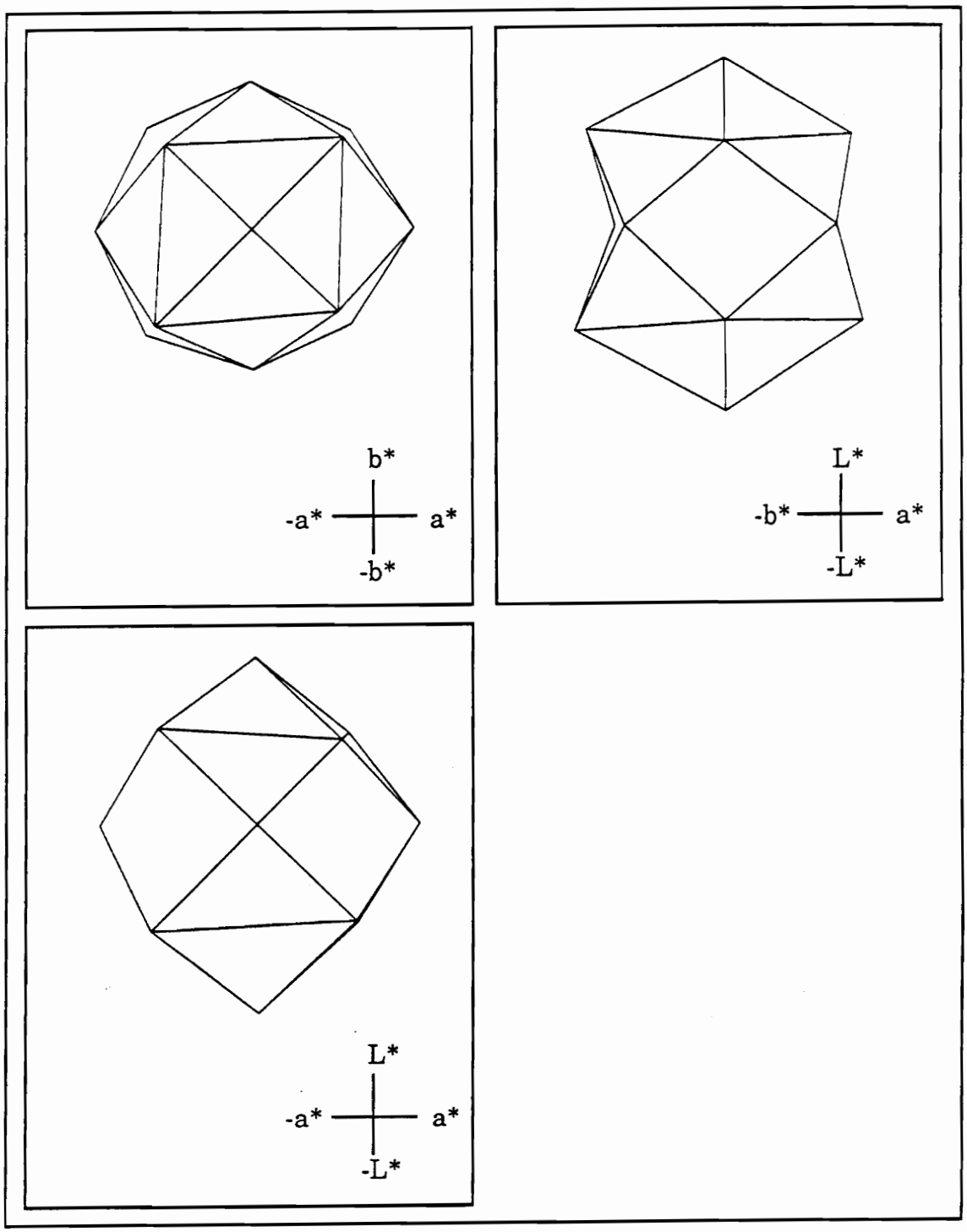

Figure F-9. Perceived color-difference plot: Green, 10ΔE, Expert.

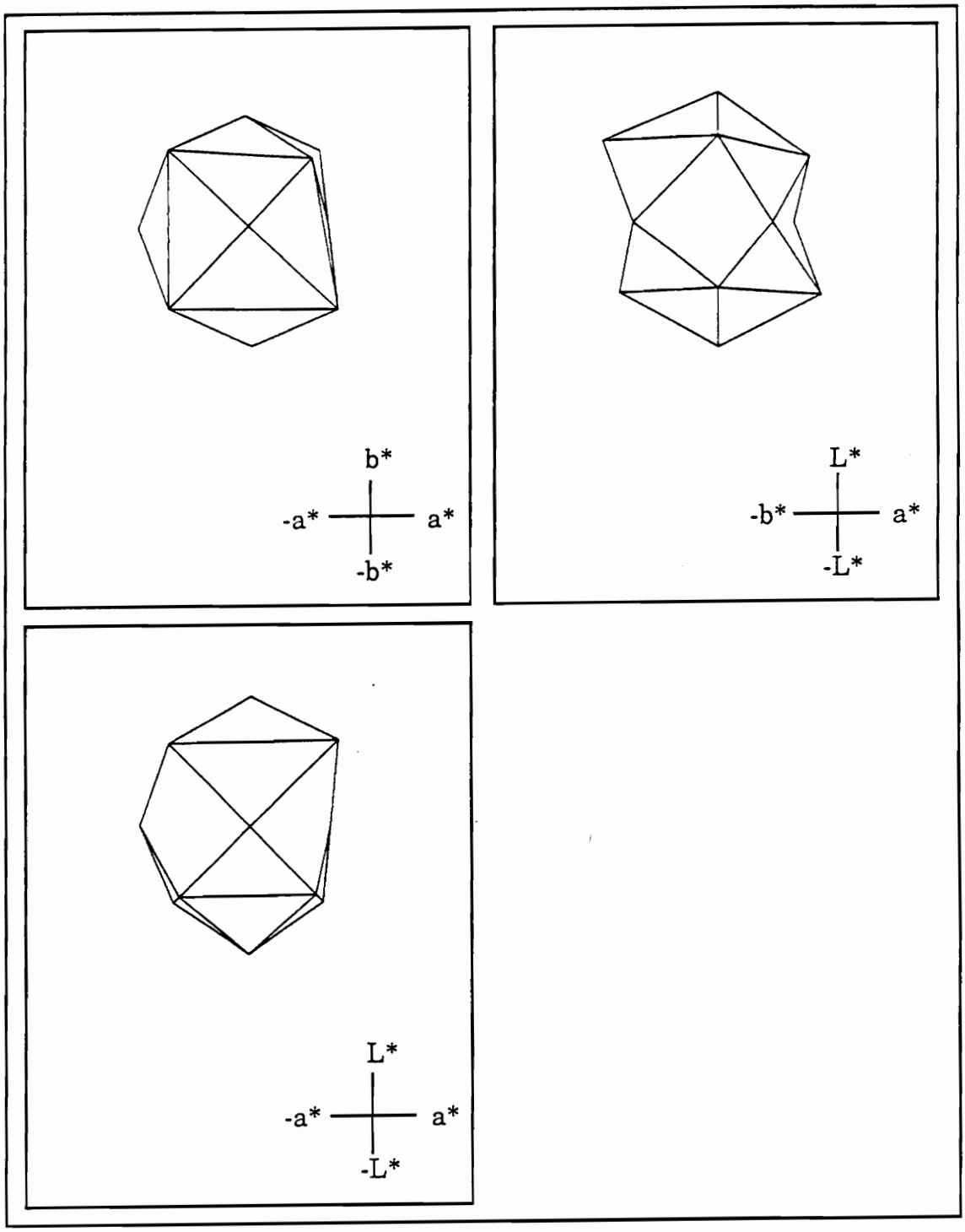

Figure F-10. Perceived color-difference plot: Red, 5ΔE, Novice.

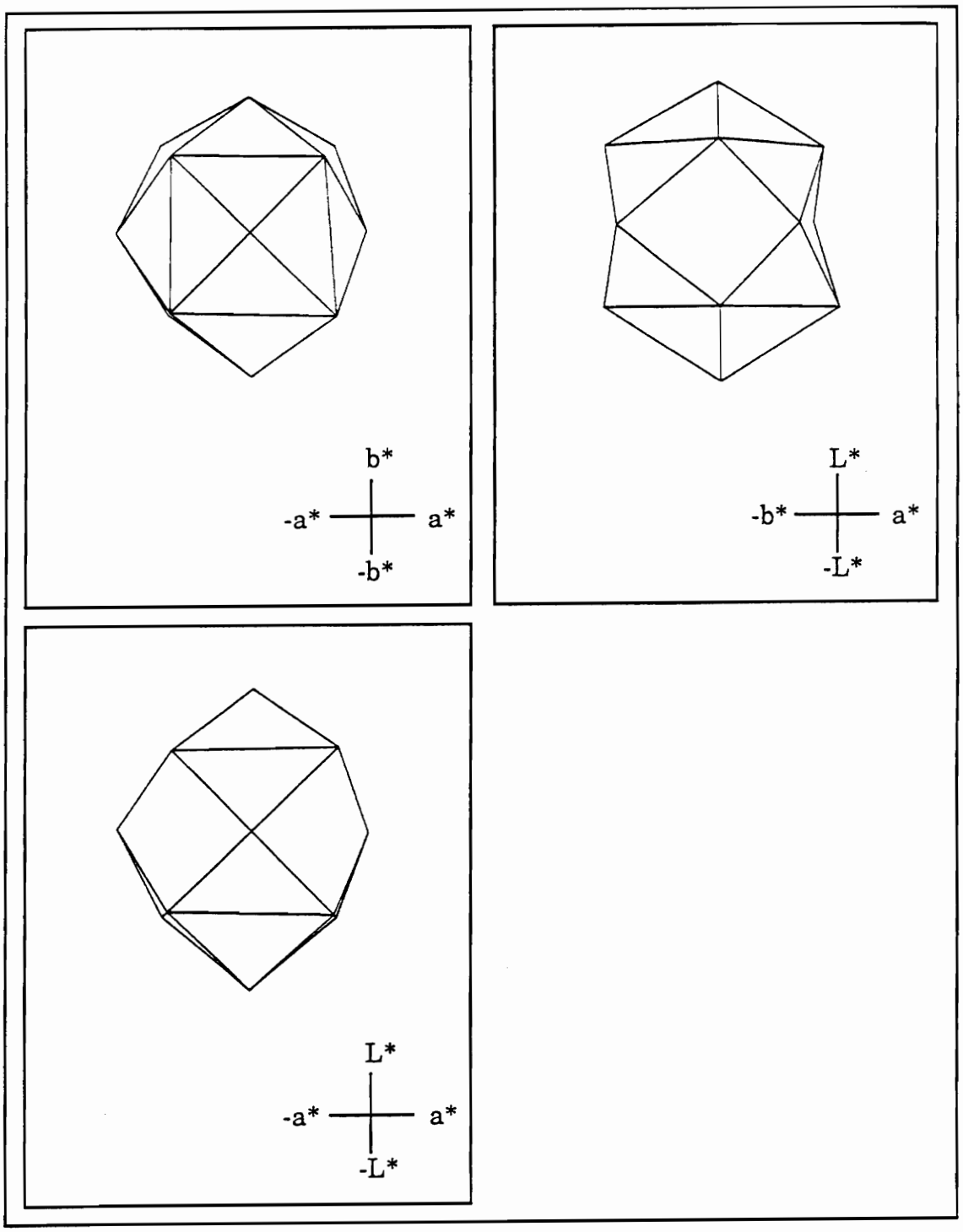

Figure F-11. Perceived color-difference plot: Red, 5ΔE, Expert.

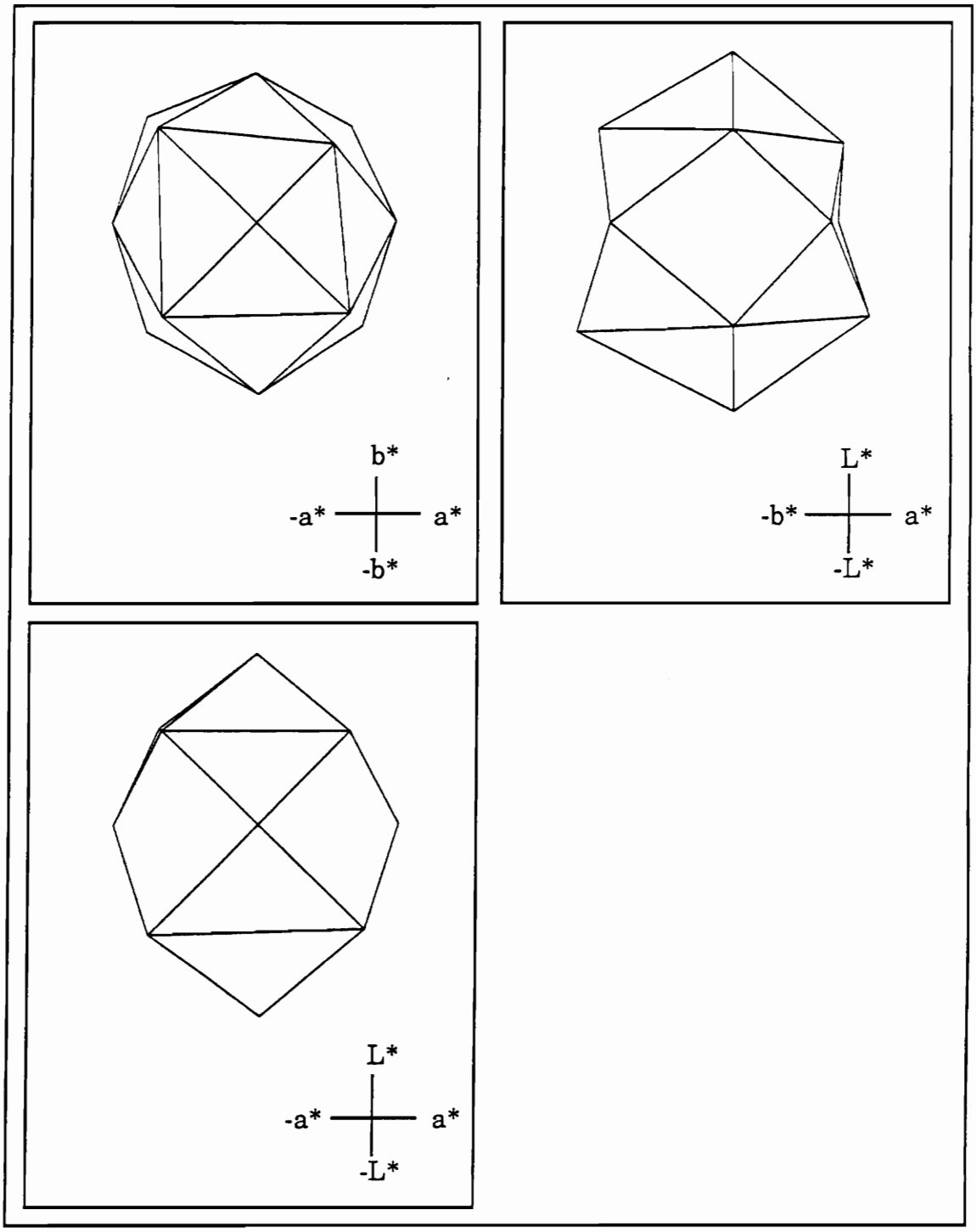

Figure F-12. Perceived color-difference plot: Red, 10ΔE, Novice.

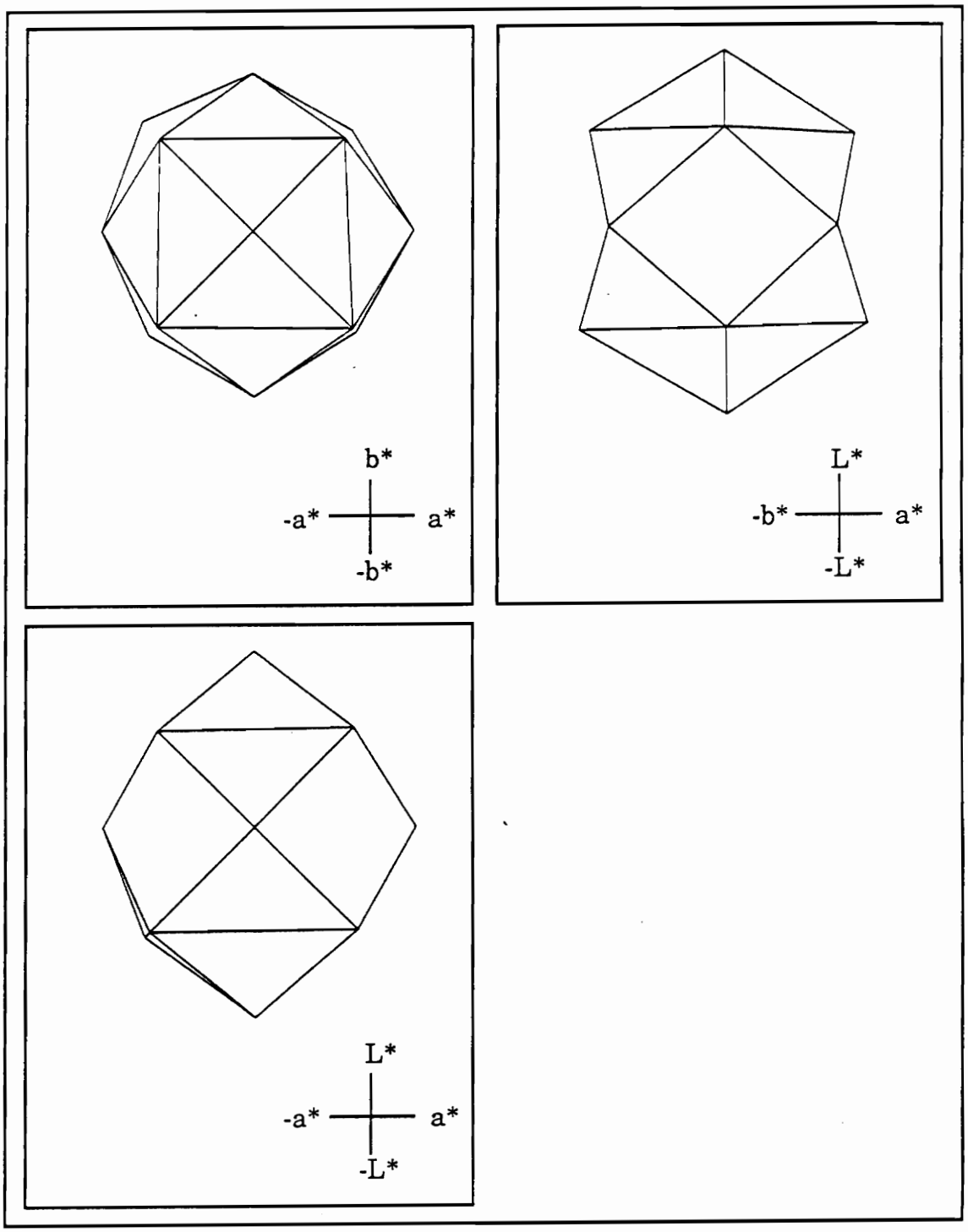

Figure F-13. Perceived color-difference plot: Red, 10ΔE, Expert.

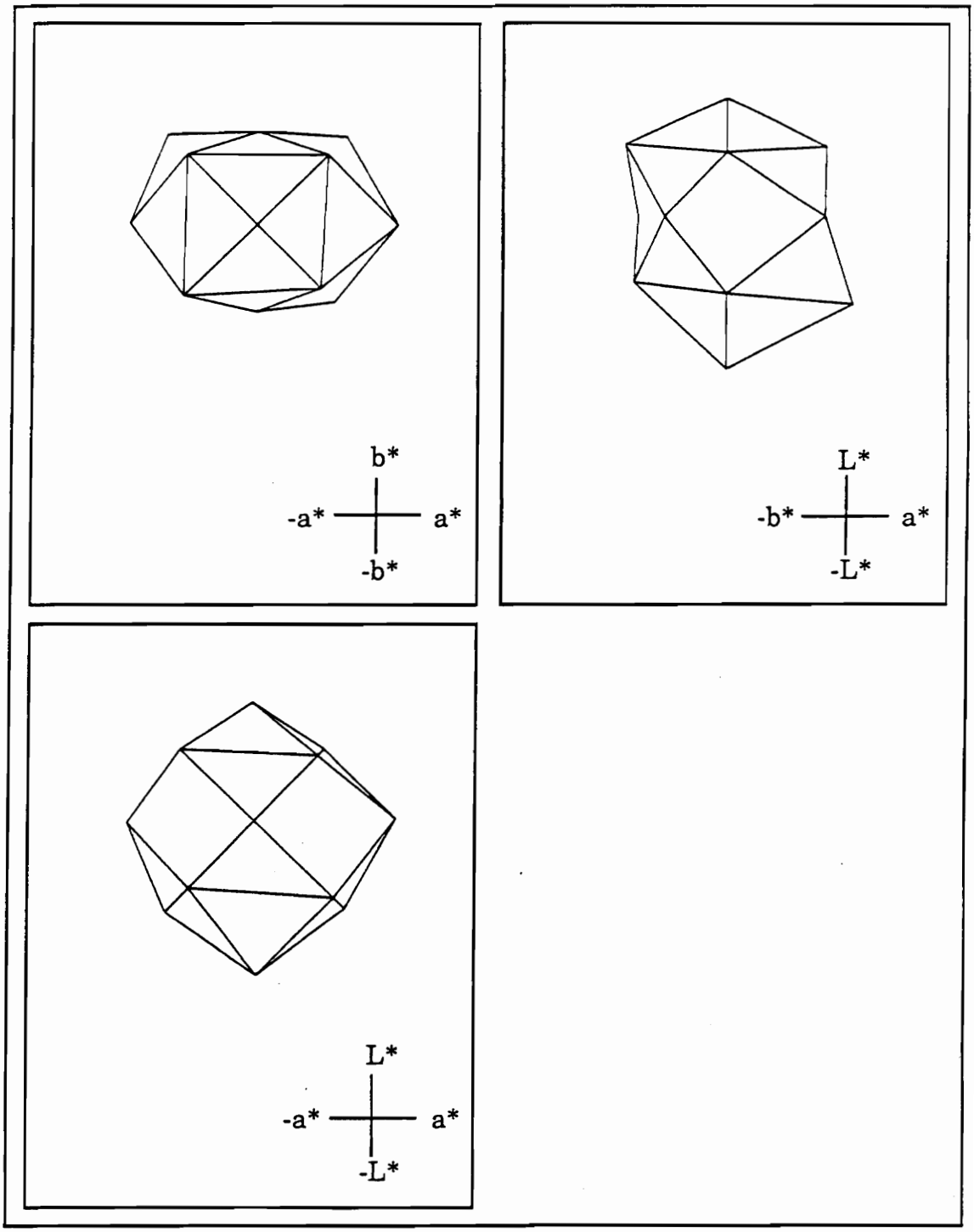

Figure F-14. Perceived color-difference plot: Blue, 5ΔE, Novice.

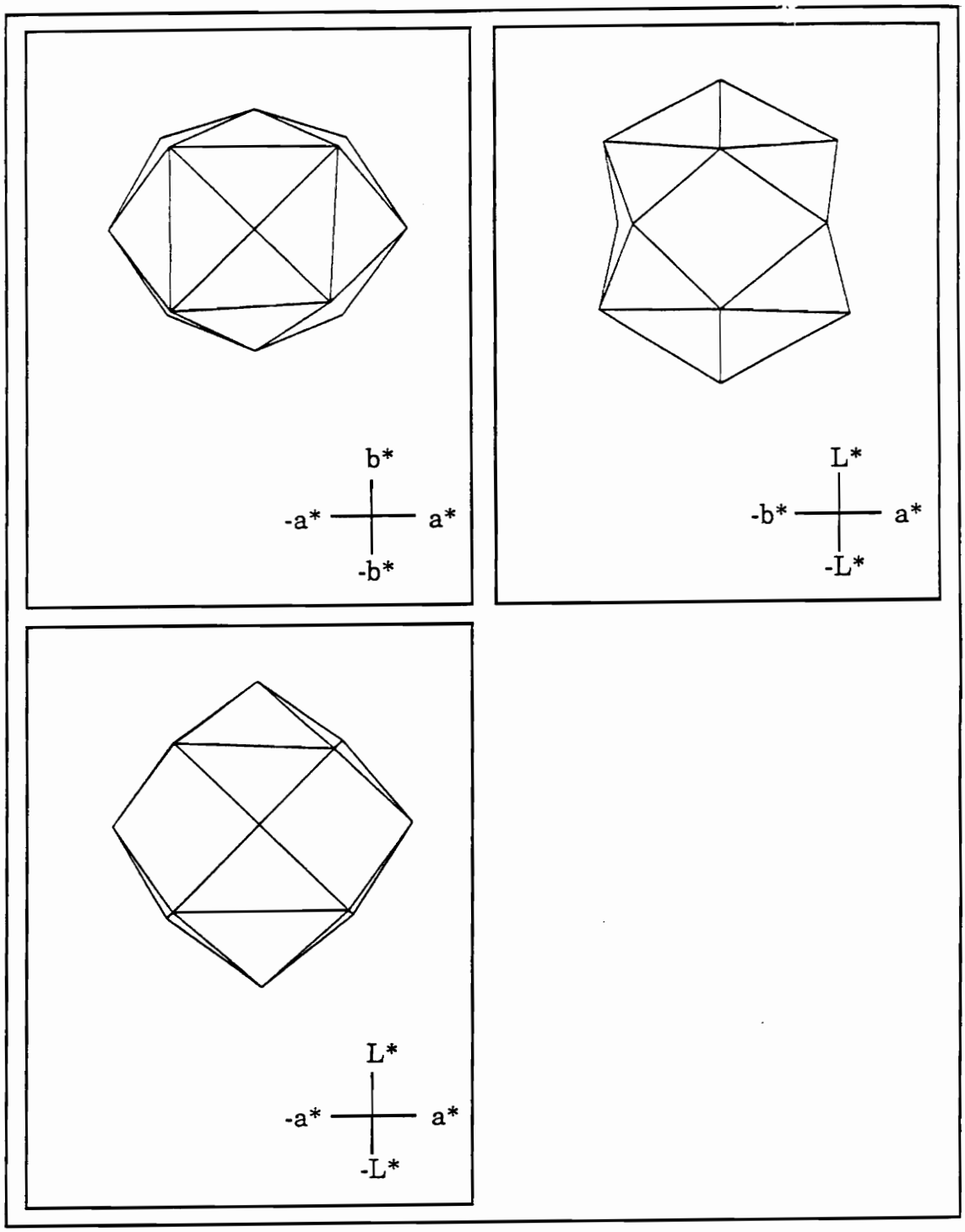

Figure F-15. Perceived color-difference plot: Blue, 5ΔE, Expert.

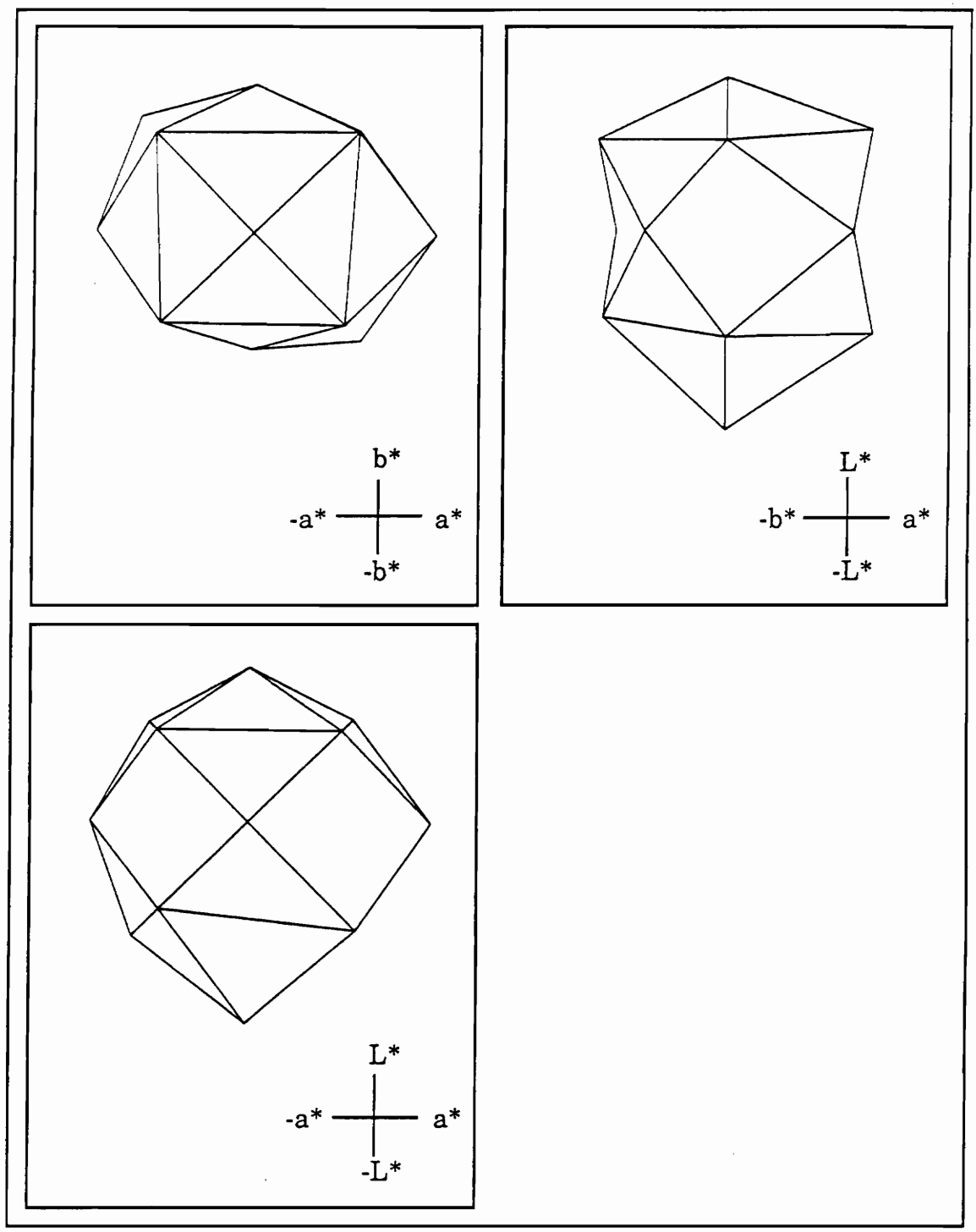

Figure F-16. Perceived color-difference plot: Blue, 10ΔE, Novice.

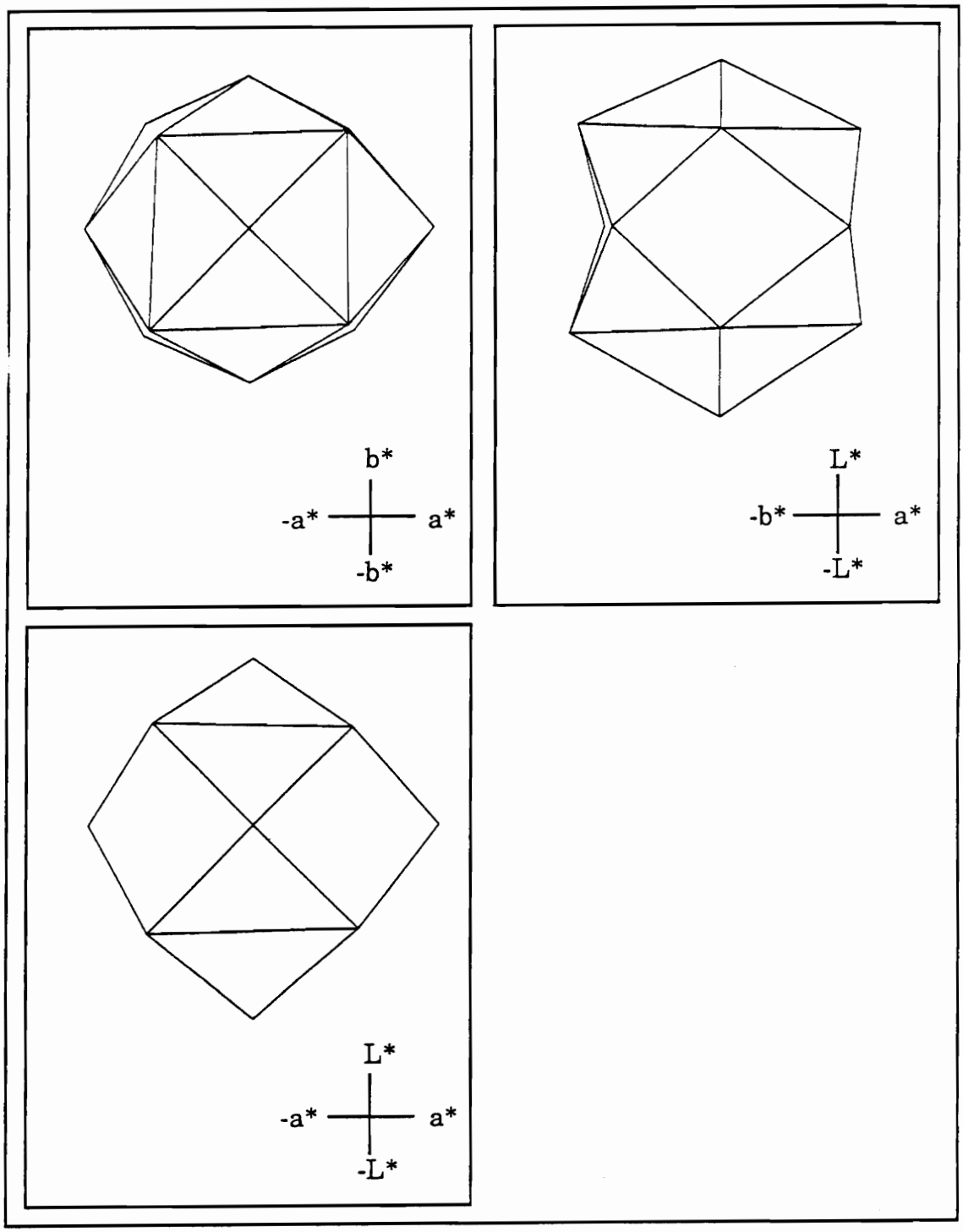

Figure F-17. Perceived color-difference plot: Blue, 10ΔE, Expert.

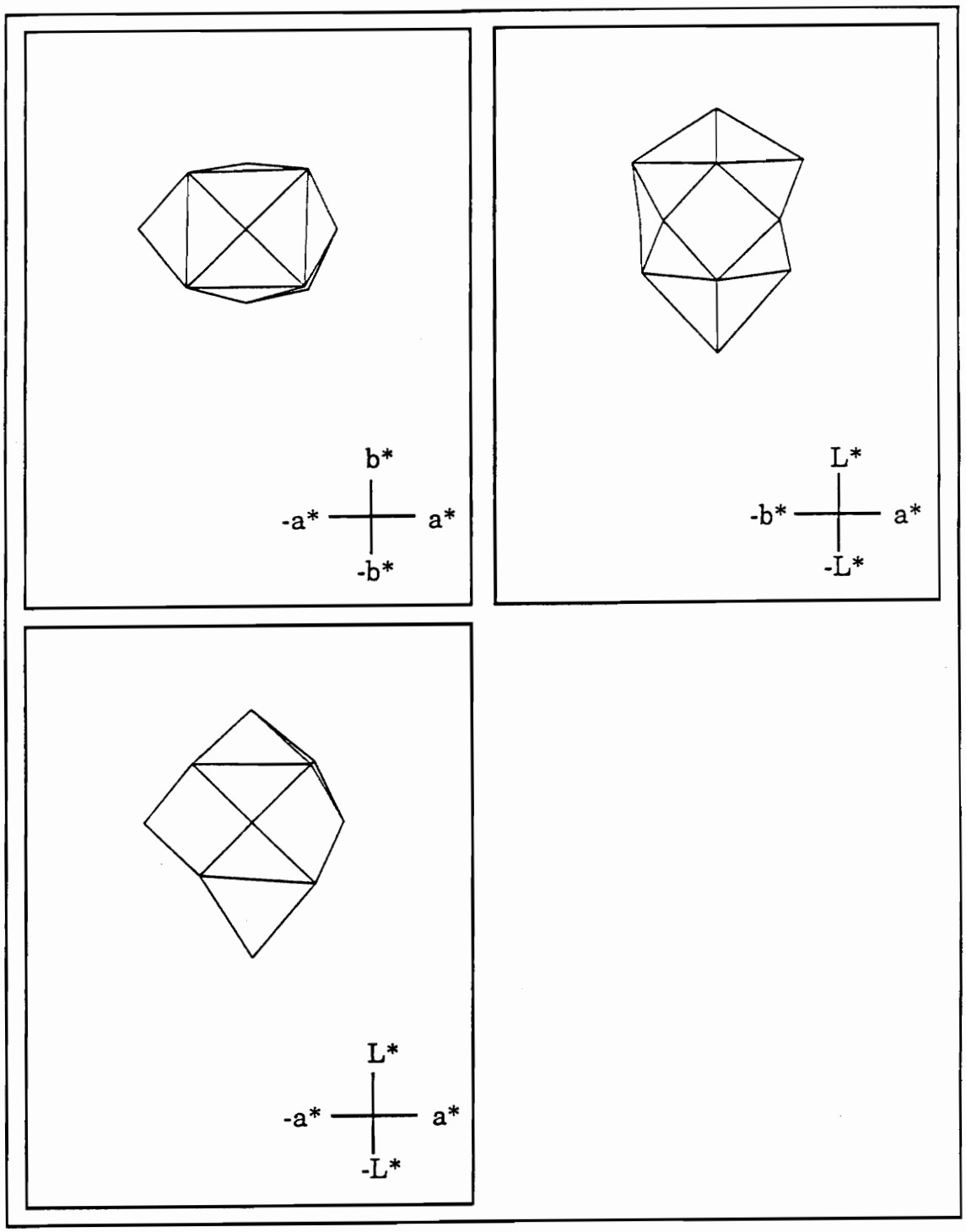

Figure F-18. Perceived color-difference plot: Yellow, 5ΔE, Novice.

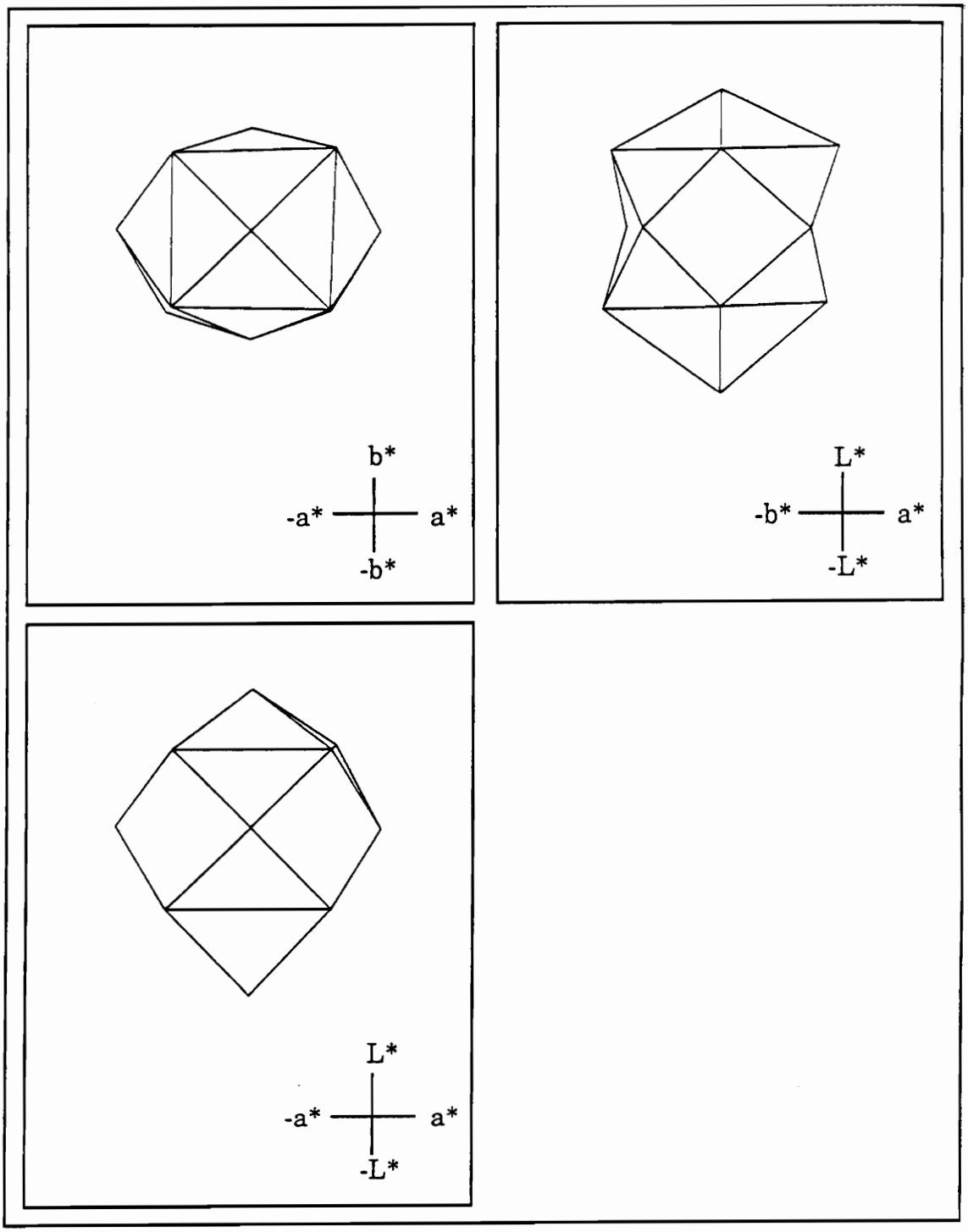

Figure F-19. Perceived color-difference plot: Yellow, 5ΔE, Expert.

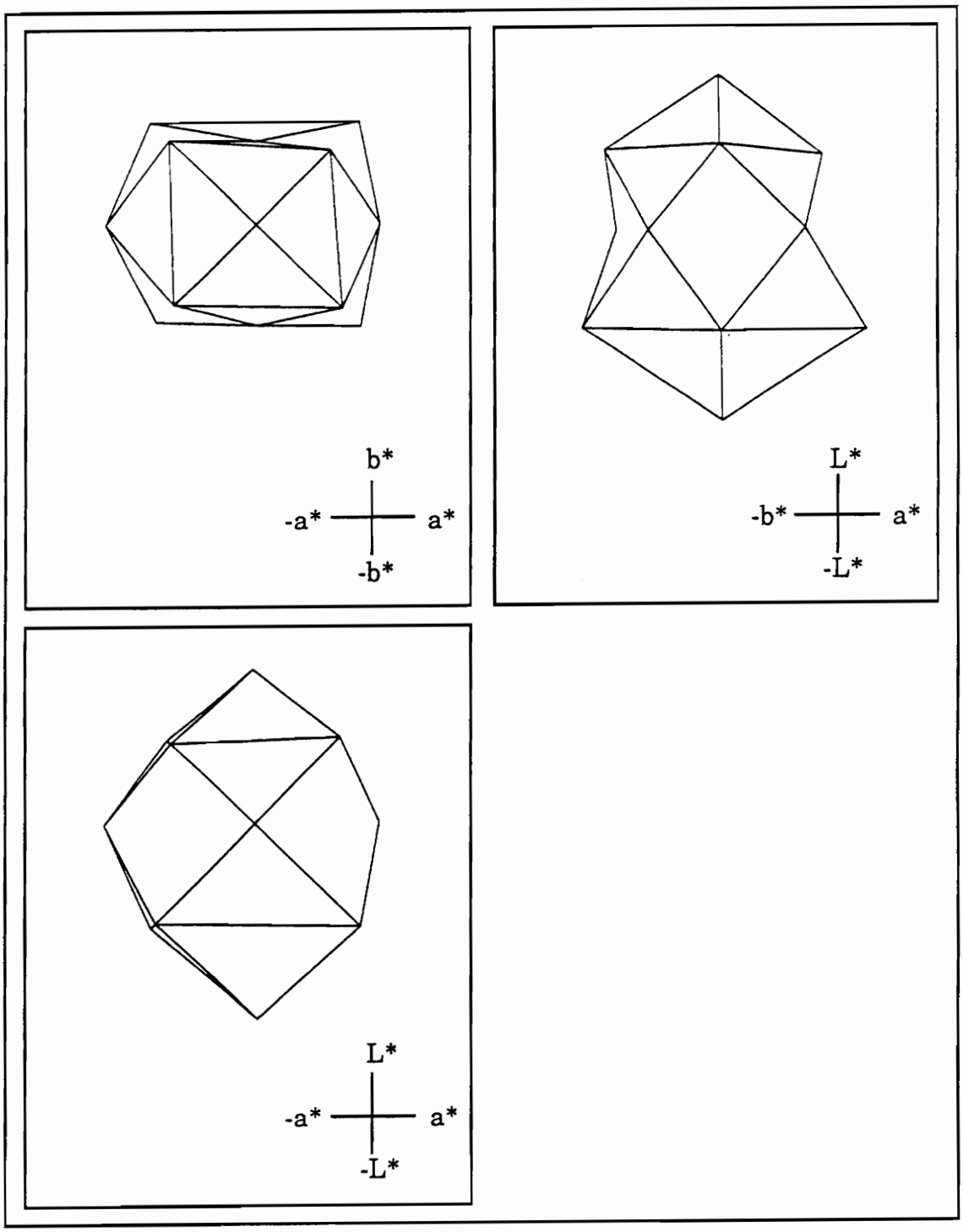

Figure F-20. Perceived color-difference plot: Yellow, 10ΔE, Novice.

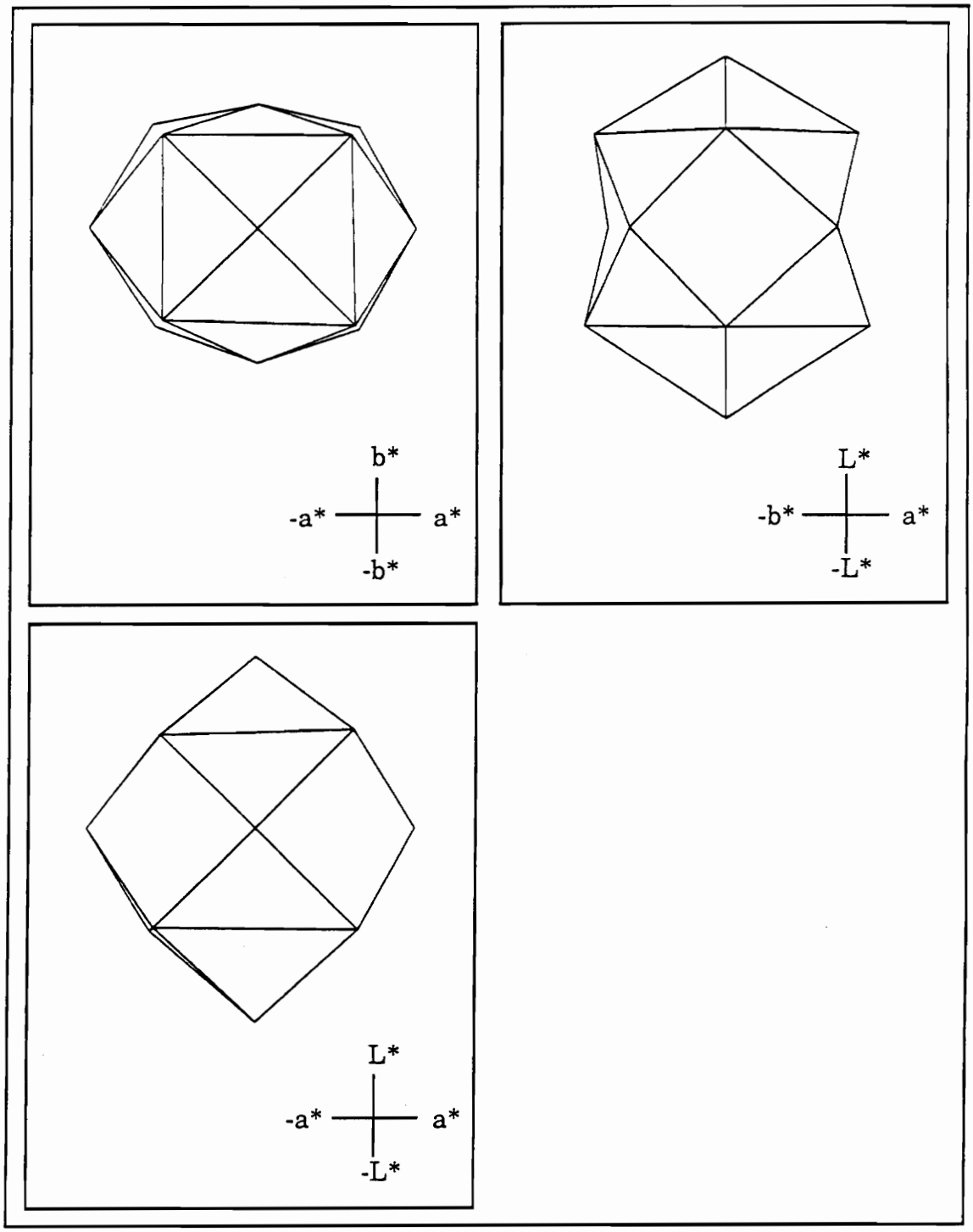

Figure F-21. Perceived color-difference plot: Yellow, 10ΔE, Expert.

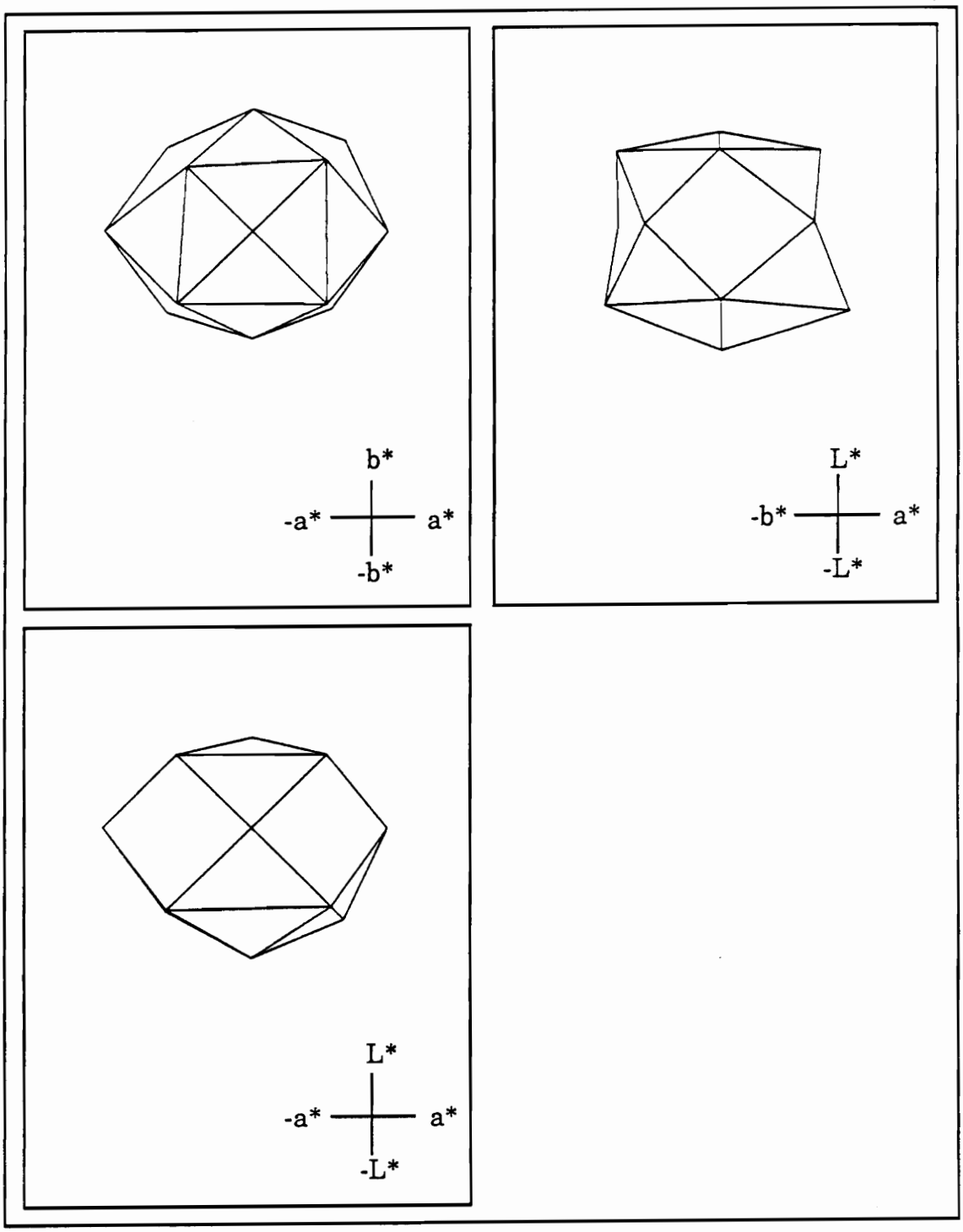

Figure F-22. Perceived color-difference plot: Neutral, 5ΔE, Novice.

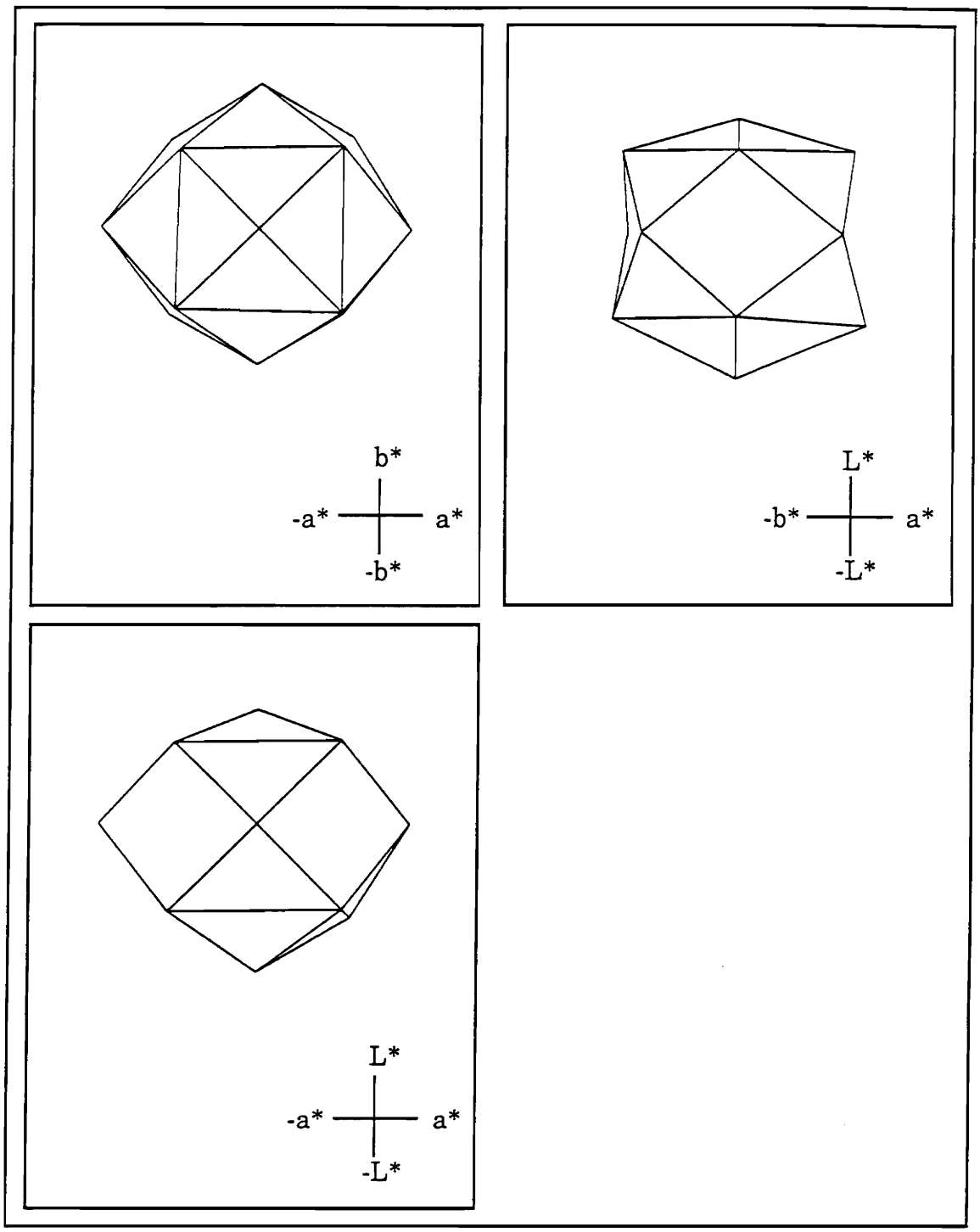

Figure F-23. Perceived color-difference plot: Neutral, 5ΔE, Expert.

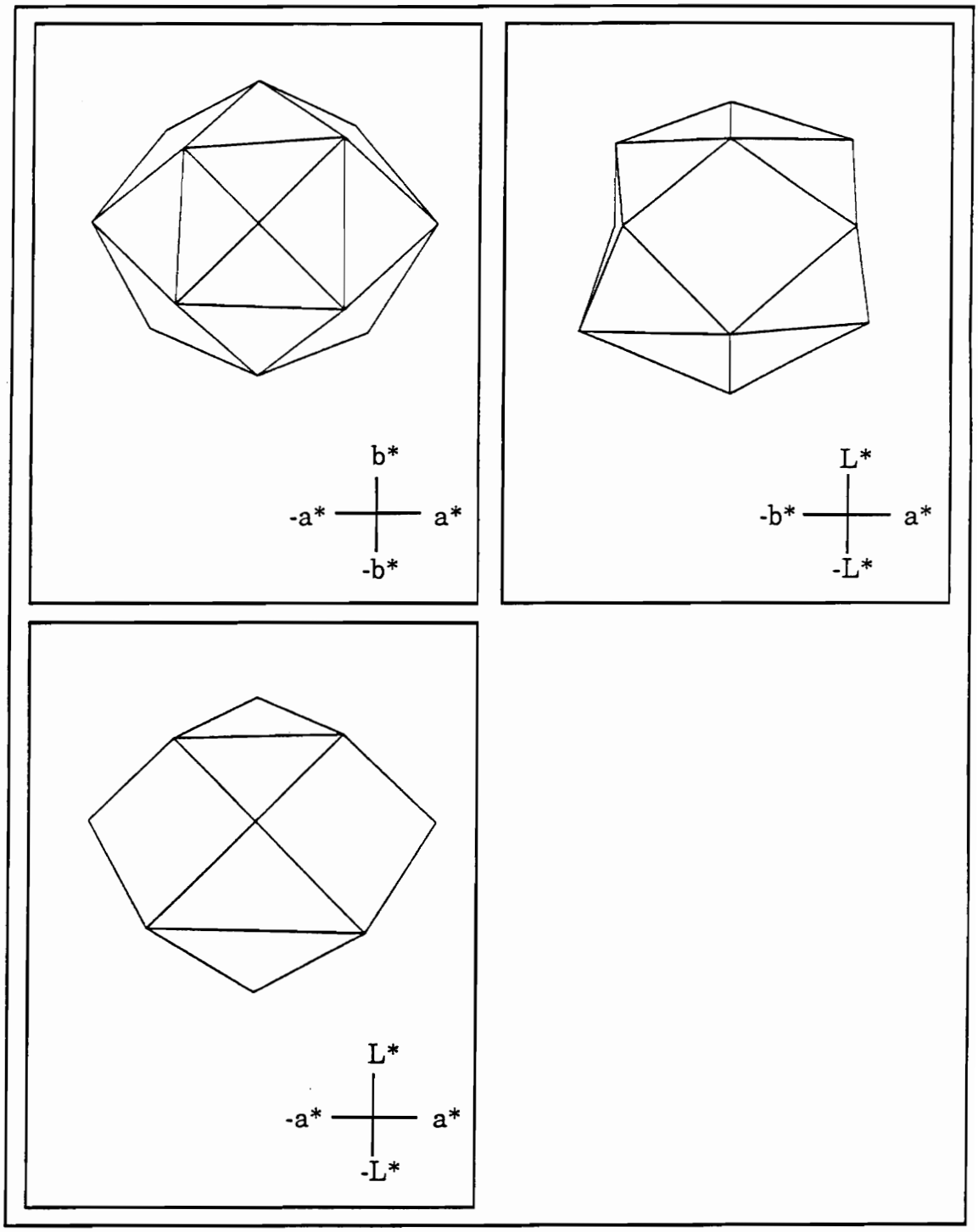

Figure F-24. Perceived color-difference plot: Neutral, 10ΔE, Novice.

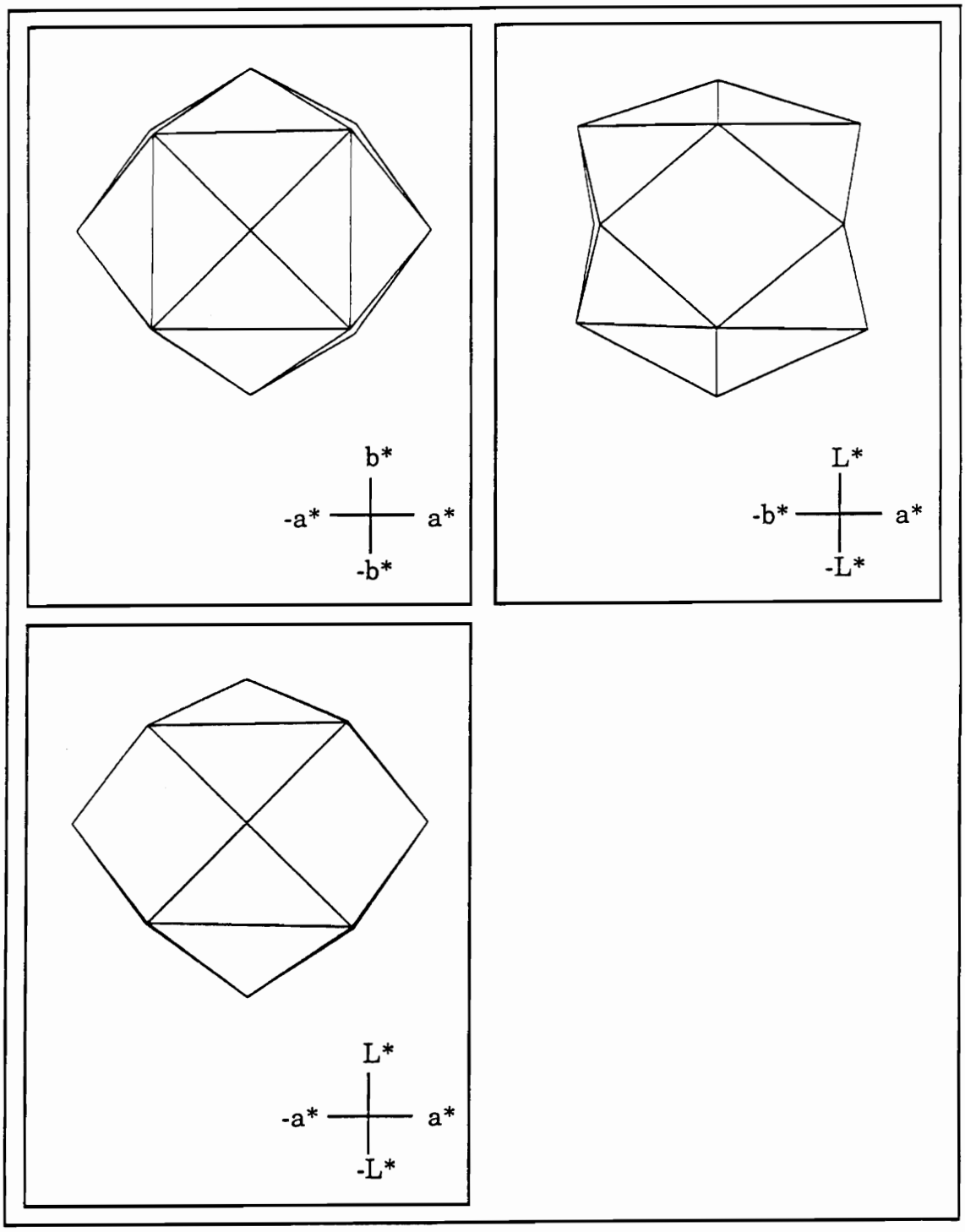

Figure F-25. Perceived color-difference plot: Neutral, 10ΔE, Expert.

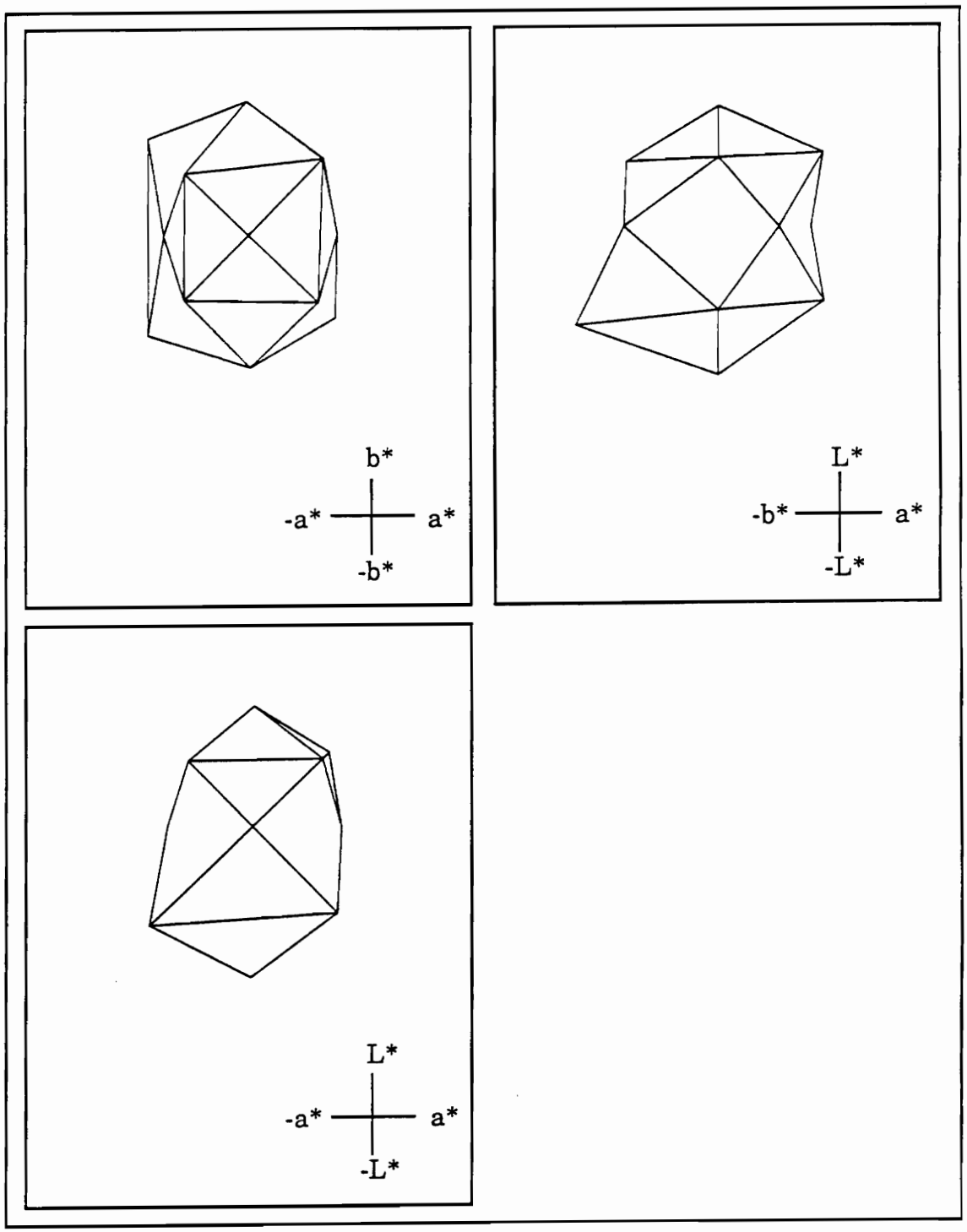

Figure F-26. Perceived color-difference plot: Cyan, 5ΔE, Novice.

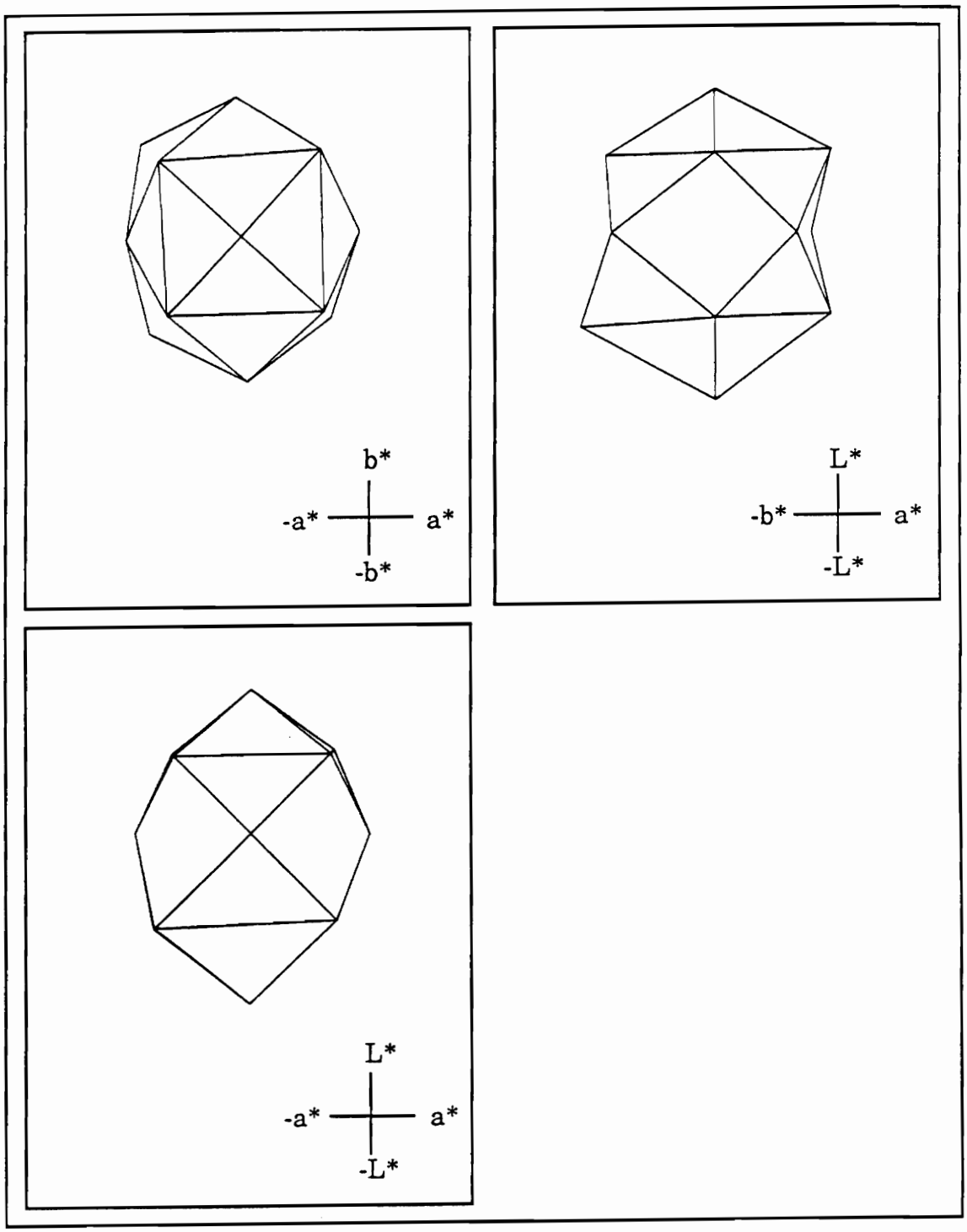

Figure F-27. Perceived color-difference plot: Cyan, 5ΔE, Expert.

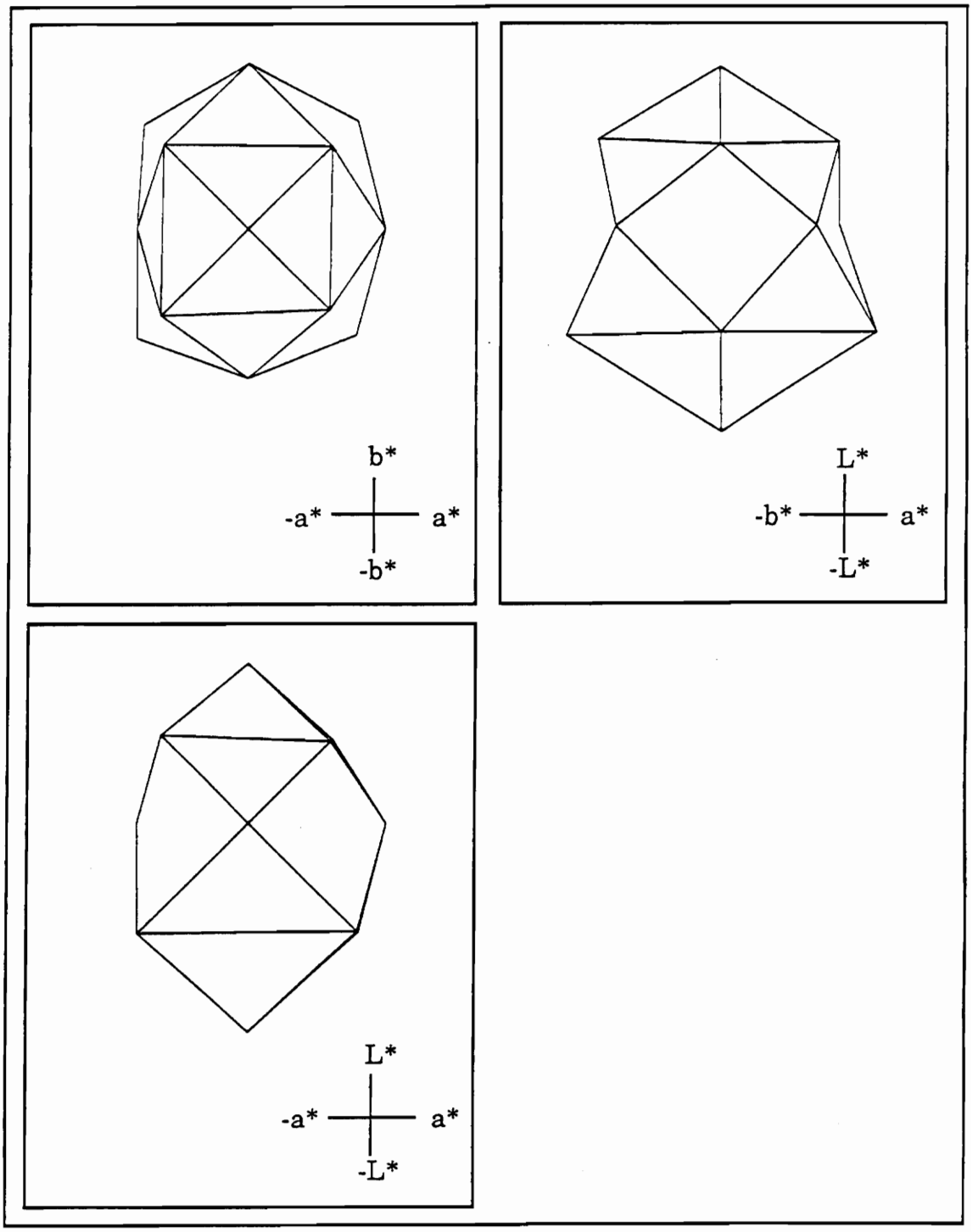

Figure F-28. Perceived color-difference plot: Cyan, 10ΔE, Novice.

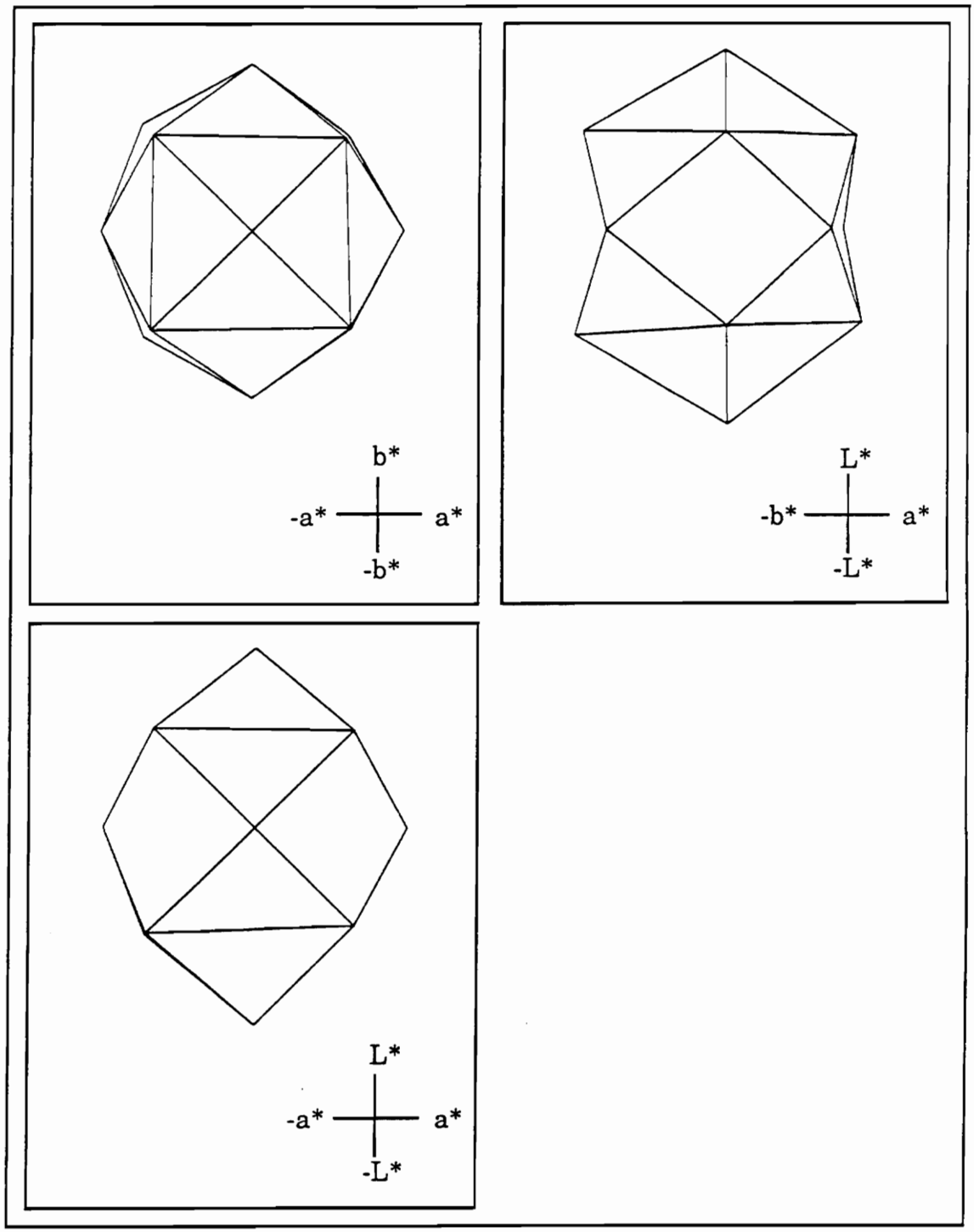

Figure F-29. Perceived color-difference plot: Cyan, 10ΔE, Expert.

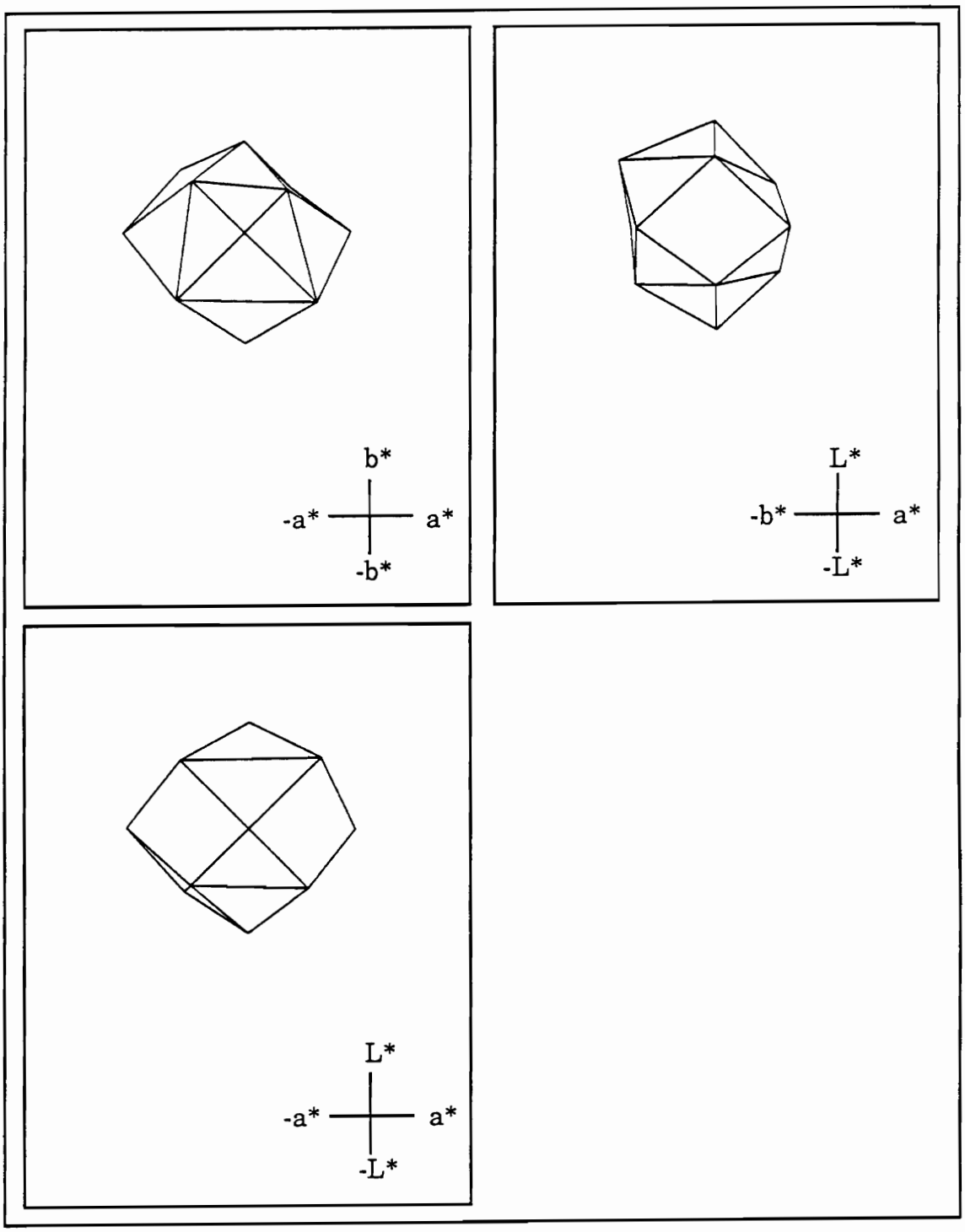

Figure F-30. Perceived color-difference plot: Caucasian, 5ΔE, Novice.

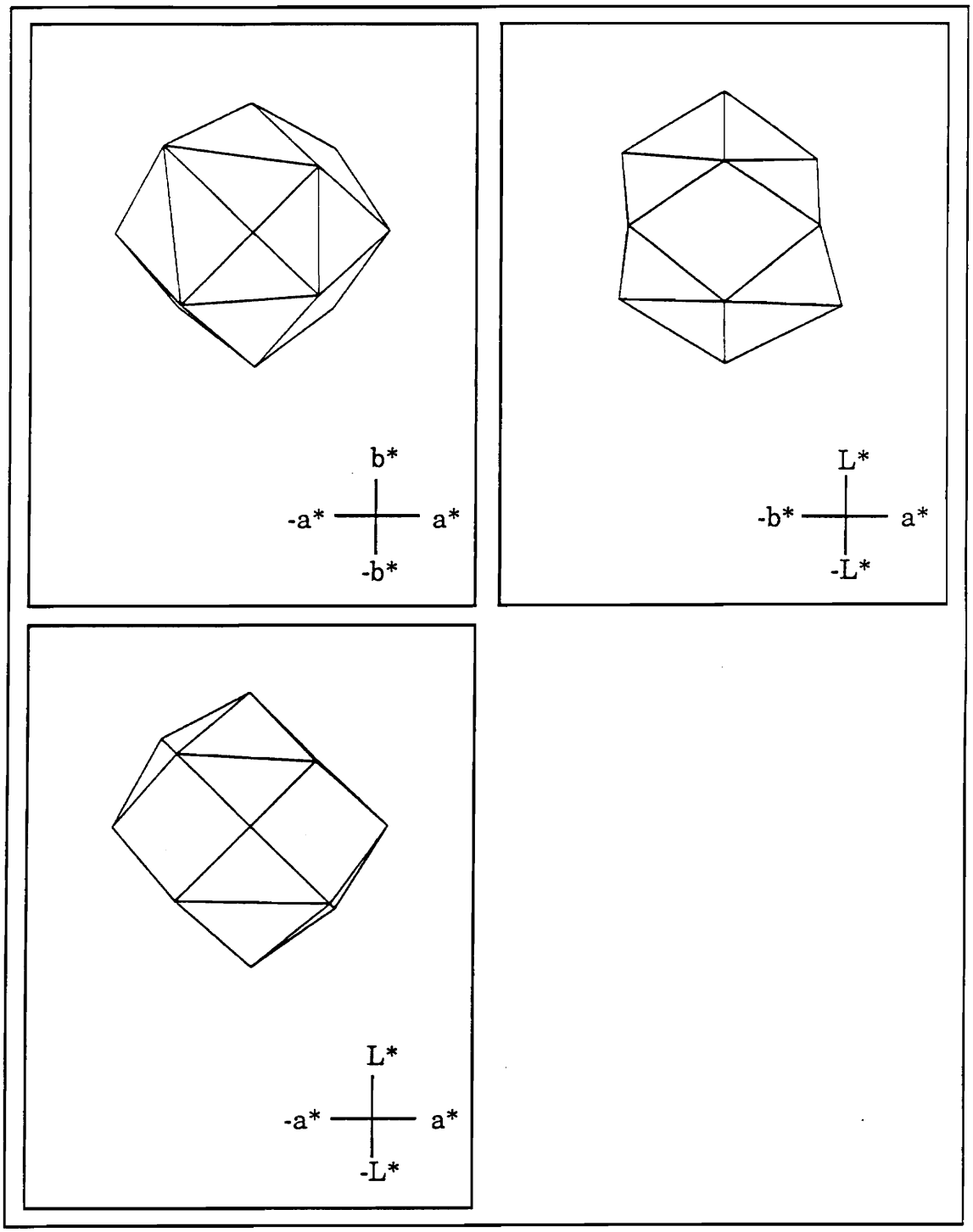

Figure F-31. Perceived color-difference plot: Caucasian, 5ΔE, Expert.

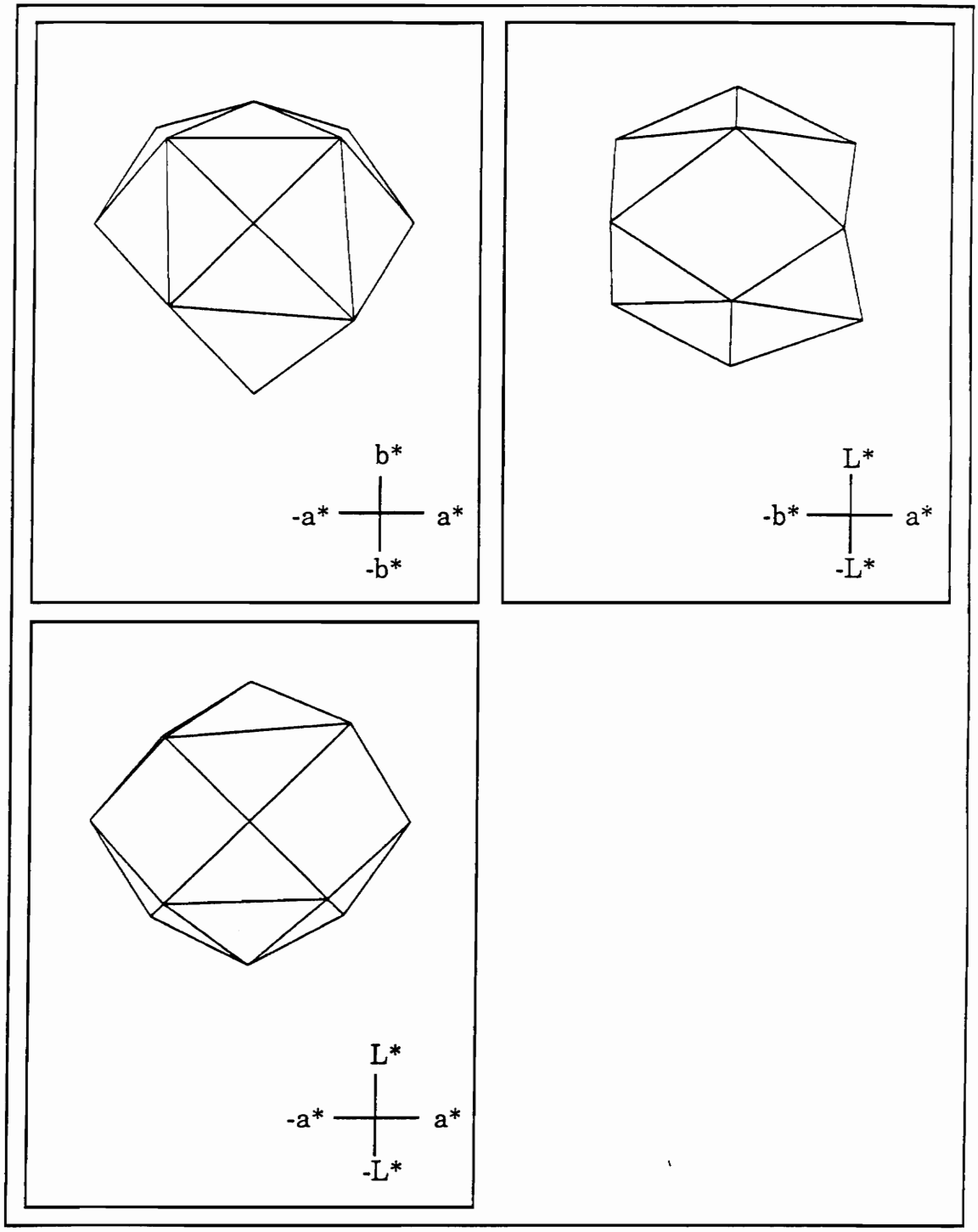

Figure F-32. Perceived color-difference plot: Caucasian, 10ΔE, Novice.

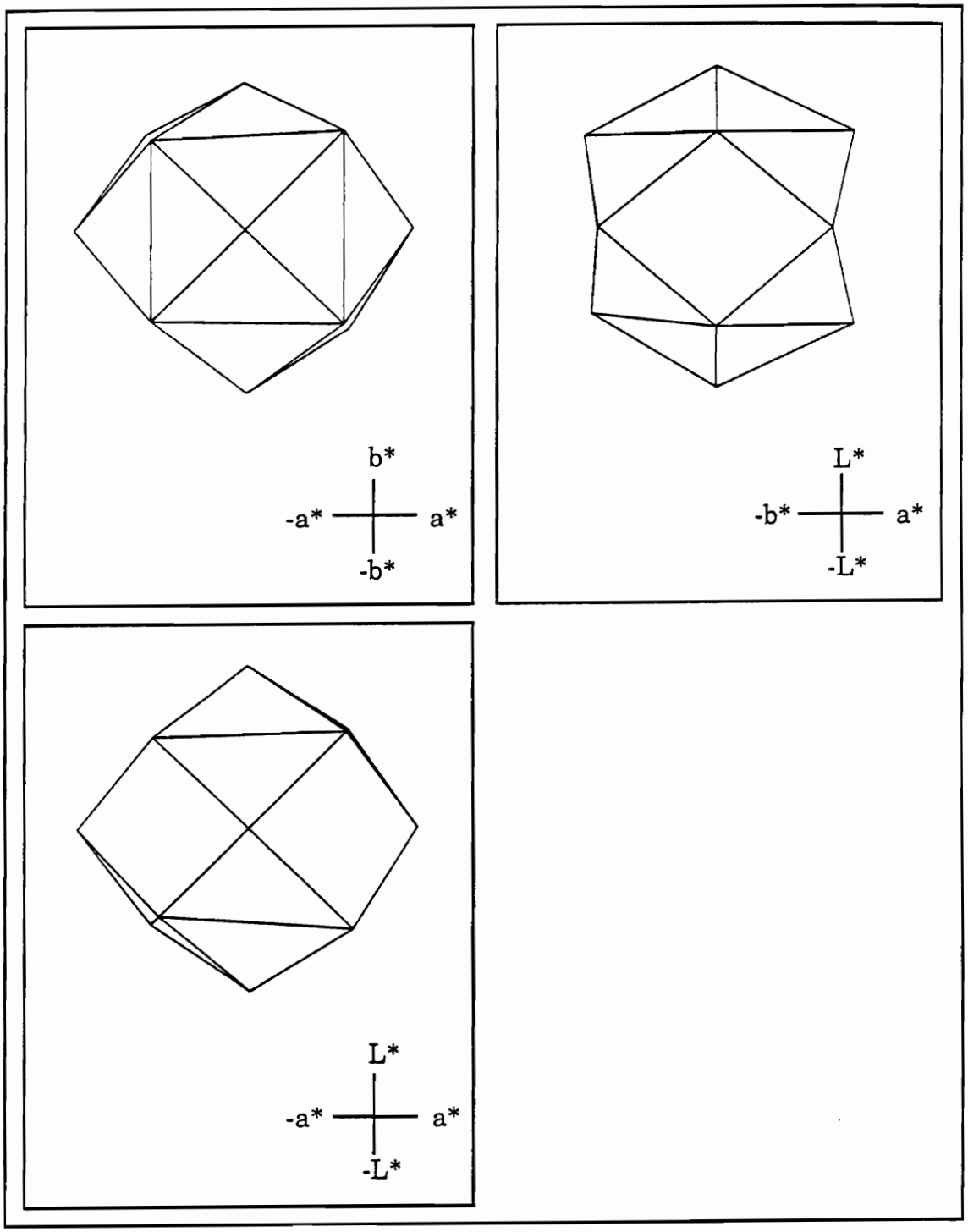

Figure F-33. Perceived color-difference plot: Caucasian, 10ΔE, Expert.

VITA

James Richard Sayer was born on the seventeenth of February, 1963 in Detroit, Michigan. He received a Bachelor of Science degree in psychology from the University of Michigan in 1988. While at Michigan, James assisted in research concerning visual and auditory psychophysics, as well as human factors engineering of automotive displays. At Virginia Polytechnic Institute and State University his work has concentrated upon the perception of color and evaluation of color-difference formulae for application to color photographic prints and electronic displays.