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PSYCHOPHYSICS OF MODERN CAMOUFLAGE (U)

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INTRODUCTION

In October 1981 the Army began to issue the new Battle Dress Uniform. The most conspicuous feature of this garment is its Woodland Pattern that was designed to meet the Army's primary camouflage objectives for personnel in temperate regions, day and night, summer and winter.

Camouflage has the objective of reducing enemy perception of military installations, units, equipment, and personnel to enhance mission success, tactical advantage, and survival, itself, on the modern battlefield. To thwart the multiplicity and power of modern sensors, development of countermeasures can no longer rely on the intuitive methods of the past. Success in achieving the camouflage objectives for today's Army requires one to draw upon the resources of several scientific disciplines. Establishment of principles, criteria, and approaches emerges from basic understanding of relevant aspects of physics, ocular structure, psychology, and military science. Implementing the principles to produce real meterials is primarily the task of chemistry and industrial technology.

This paper describes the application of psychophysical principles that led to the development of the Woodland Pattern. The scientific discipline that unifies the relevant physics, anatomy, and psychology of vision is called psychophysics. This is defined as "the branch of psychology that deals with relationships between physical stimuli and the resulting sensations and mental states"(1). For the purposes of this paper, the physical stimulus is electromagnetic radiation in the visible and near-infrared regions of the spectrum; the resulting sensations are the responses of a sensor and the person using it.

Of all the sensors a combat soldier encounters, the most versatile is the ubiquitous human eye; it is, as well, the ultimate sensor in using

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electro-optical devices. It is essential, therefore, that the design of camouflage measures be related to the visual process. In this study the camouflage objectives of the development were to minimize visual perception of soldiers by day and detection by image intensifier devices at night. Although the eye is far more complex, the processes that take place in a starlight scope can be dealt with by methods similar to those used for calculations related to color vision.

VISUAL ASPECTS

In-process reviews that led to the Required Operational Capability (ROC) document concluded that the shapes of individual elements of the camouflage pattern should be the same as those used in the tropical uniform that has been in the supply system for many years. Based on earlier field trials, the reviews also decided that the overall size of the pattern should be enlarged by 60 per cent compared to the older pattern(2). It was also believed that small changes in color from the earlier pattern would improve camouflage effectiveness for year-round use in temperate regions. The four colors of the new pattern are designated Light Green, Dark Green, Brown, and Black.

Selection of Colors

Application of psychophysical principles to questions of camouflage clothing began shortly after World War II. Extensive field trials demonstrated that Olive Drab field uniforms should be replaced by a greener color. The new target color, Olive Green (OG), was defined in Munsell terminology as 10Y3/3(3). Development of the standard OG color on fabrics of many kinds was guided by familiar colorimetric procedures(4). Selection of OG for monotone camouflage clothing and shelters has stood the test of time; it is still the US standard monotone field color for such items in both temperate and cold regions. Moreover, most nations have adopted very similar colors for these purposes. A more detailed historical review of the development of camouflage coloration is given in Reference 5.

During WW II the US Marines made some use of camouflage patterns for clothing in the Pacific, but it was not until the Vietnam era that the US Army did so for a tropical uniform. This uniform used a camouflage pattern that had been designed in 1948 by the Engineer R&D Laboratory (ERDL). Combat experience in Vietnam, however, proved that this design was too bright. Accordingly, the colors were toned down by Natick Laboratories in such a manner that the merged color more nearly approximated the OG color standard. The standard for this pattern is called NIABS-1; when that standard was depleted in 1979, a replacement was chosen, NIABS-2.

The merged color is that seen when a pattern is observed at a sufficient distance that the individual color elements can no longer be resolved by the eye. The method for calculating the merged color of a pattern is based on a summation of tristimulus values for each color, weighted by the

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fractional area in the pattern represented by each color, as described in Reference 5.

Because the Woodland pattern is intended to be used in temperate areas during both dormant and verdant seasons, colors were chosen so the merged color is somewhat duller than the OG target color, and closer in chroma to Forest Green, a monotone adopted by the Army for use on vehicles and other field items. In the design of surveillance countermeasures, the primary objective is reduction of contrast between the object to be protected and its surrounding background. For visual camouflage, where chromatic colors are used, quantitative measures of color difference as described in Reference 4 are generally employed to define contrast. Figure 1 shows the hue and the chroma in CIELAB color space for OG, Forest Green, the merged colors for ERDL, the two toned down versions (NLABS-1 and 2), and the Woodland pattern.

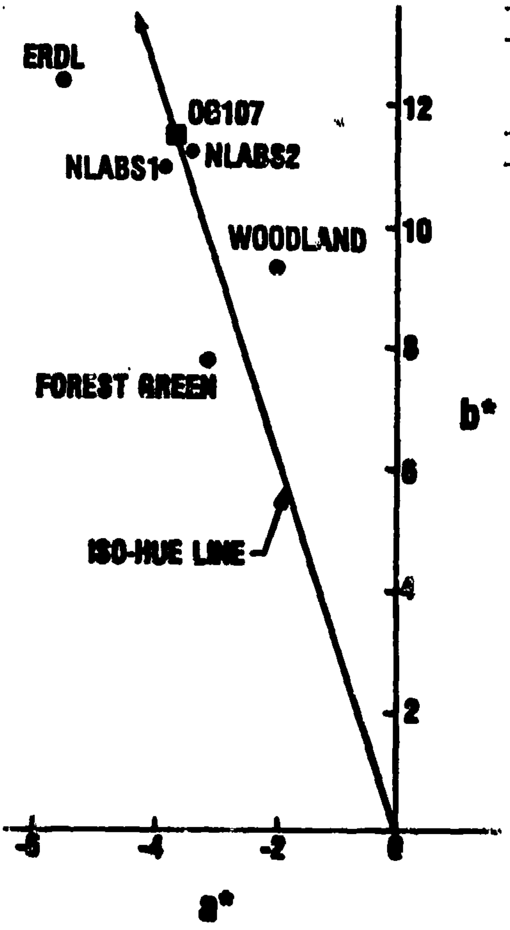

Figure 1. Chromaticity diagram for OG and Forest Green monotones and the merged colors for ERDL, NLABS-1, NLABS-2, and Woodland patterns.

Effective Range

A second factor in selecting the specific color for each of the pattern elements was based on the ability of the eye to resolve the individual areas. The assumption was made that, for the pattern to be effective it must be seen as a pattern; otherwise it would perform no differently than an equivalent monotone.

Fundamental to an understanding of how well the eye copes with this question is a knowledge of the structure of the retina. Figure 2 is a photograph of the central portion of a normal retina. The bright area near the edge of the image is the visually inert optic nerve. The darker region near the center is called the macula lutea, a region with greatly increased concentration of cones and depletion of rods. In the center of the macular region is located a small, diffusely defined depression called the fovea centralis, an area about 0.5 mm in diameter. This rod-free region of the retina contains about 50,000 cones. This is the retinal region of maximum color difference

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Figure 2. Normal macula.

discrimination and acuity. A more thorough description of this, the most important area of the retina, is given in Reference 6.

A typical element of the Woodland pattern may be 20 cm by 5 cm. When observed at 200 m, this element subtends an angle at the retina of only one milliradian (mr) by 0.25 mr and produces an image about 16 μm by 4 μm. Within this small image there will be only three to five cones of each of the three types; green-, red-, and blue sensitive. Considering the complexity of color vision, it is not surprising that the eye experiences difficulty in distinguishing color differences among neighboring elements viewed at considerable distance.

It has long been known qualitatively that small target colors give the eye greater difficulty in discriminating yellow-blue differences, approximately the b axis in Figure 1, than it does red-green or lightness differences. This phenomenon has been called "small angle tritanopia." Under such conditions of viewing, normal observers respond in a manner similar to one kind of color blindness, tritanopia. König reported studies of this as long ago as 1894 (7); among several more recent studies is that reported by MacAdam (8). In 1946 Blackwell reported an extensive study of contrast threshold for achromatic targets, thereby establishing a sound basis for dealing quantitatively with differences in lightness (9).

Judd and Yonemura (1969) reported a study of the small angle color discrimination problem in a manner that permits one to deal with all three axes in color space (10). Their method is based on u, v, W color space in which the axes are similar to, but not identical with, the a*, b*, L* axes otherwise used in this paper. Total color difference, ΔE, in this system is defined in Reference 4 as

$$\Delta E = (\Delta u^2 + \Delta v^2 + \Delta W^2)^{\frac{1}{2}} \qquad (1)$$

For small angles of view, they found that Equation 1 needed to be modified as follows

$$\Delta E' = \left[(k_2 \Delta u)^2 + (k_3 \Delta v)^2 + (k_1 \Delta W)^2\right]^{\frac{1}{2}} \qquad (2)$$

The significant contribution of the paper by Judd and Yonemura was the experimental determination of the dependence of the k-factors as functions of angular subtense. Figure 3 is adapted from their data by converting minutes of arc to the more convenient milliradians. By their modified equation, differences in the perceived colors of remote objects can be judged, regardless of their direction in color space. For example, for a

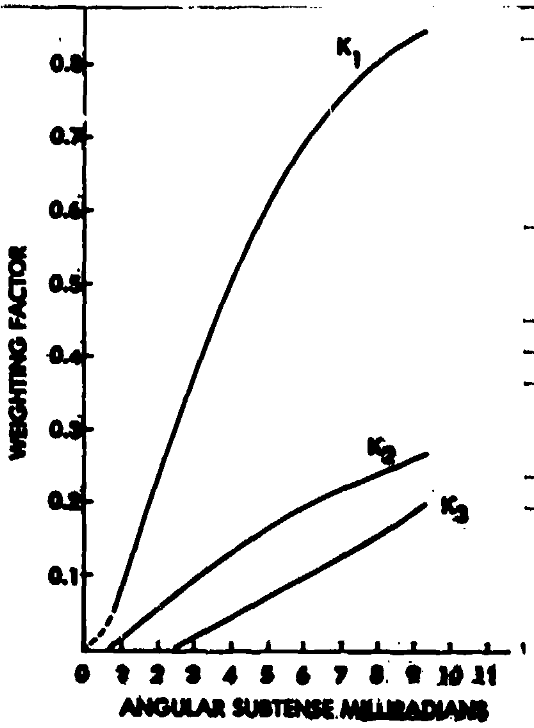

Figure 3. Dependence of K_1, K_2, and k_3 on angular subtense.

target that subtends 2 mr (a typical element of the Woodland pattern at 100 m) $k_3 = 0$; that is, the eye cannot distinguish any color differences along the yellow-blue axis of color space. Moreover, under these conditions k_1 and k_2 equal 0.22 and 0.05, respectively; only large lightness and red-green differences can be seen.

To estimate observation ranges at which the four-color pattern can actually be seen as four colors, we applied the method of Judd and Yonemura for the brown and dark green areas. These two colors were chosen because they are the most similar in lightness and comprise over 60 per cent of the total pattern. The range at which all four colors merge into a single monotone was estimated by comparing the brown and light green areas. The black area was not chosen for these comparisons because the individual black elements are small and represent only about 15 per cent of the pattern area. The next darkest area is the brown; the light green portion of the pattern is the lightest. Figures 4 and 5 summarize the calculations made for both the Woodland and the tropical pattern, NLABS-2. For these calculations, the controlling dimensions of the elements used were 20 cm and 12.5 cm, respectively. Because the ranges involved are rather short, atmospheric effects have been neglected.

Four subjects who were familiar with the camouflage development and also skilled in judging small color differences viewed both patterns on a clear day. They were asked to estimate (by pacing) the ranges at which each of the four-color patterns merged into a two-color pattern. They also were asked to estimate the range at which each pattern appeared as a monotone. The averages of these observations were that the four colors of the older NLABS-2 pattern blended into a two-color, light-dark design at about 100 m and into a monotone at about 175 m. For the Woodland pattern, these ranges were estimated at 140 and 260 m.

From Figures 4 and 5, it was concluded that the color differences that the observers could perceive under the field conditions at the limiting ranges in each case was about 0.8 u,v,W unit. Color differences of this magnitude, although readily perceptible under laboratory conditions, would, in most cases be considered good "commercial matches" by the textile industry. Both calculated data and the visual observations agree that the Woodland pattern "holds" at ranges 40 to 50 per cent longer than for the NLABS-2 pattern. On the basis of these results, it is predicted that the new Woodland pattern will provide the advantages of a disruptive design at significantly longer ranges in those terrains for which it is intended than the older NLABS-2 design which it replaces.

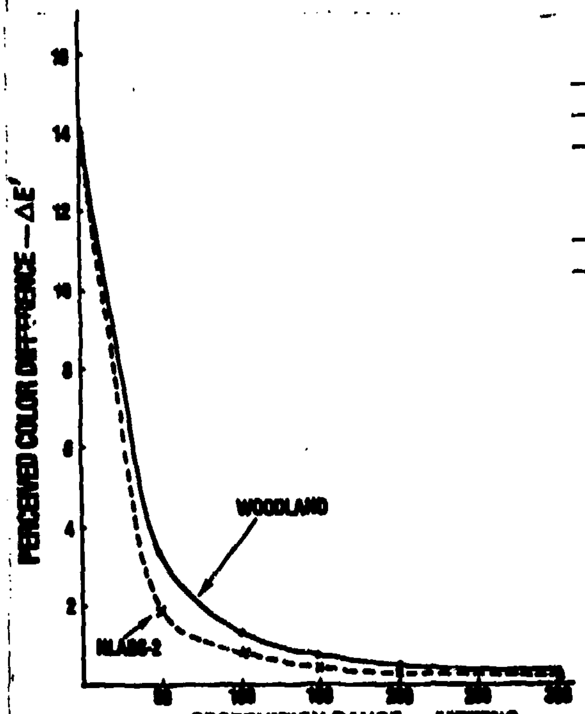

Figure 4. Perceived color differences between brown and <u>dark</u> green areas for the Woodland and NLABS-2 patterns.

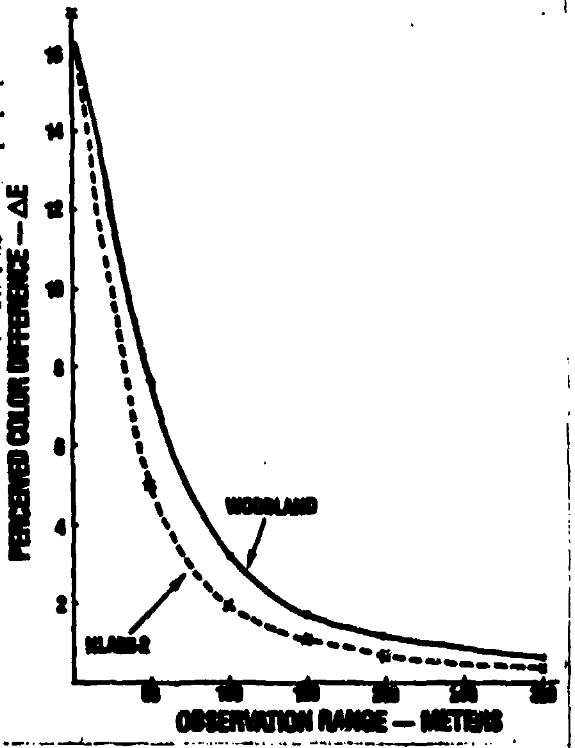

Figure 5. Perceived color differences between brown and <u>light</u> green areas for the Woodland and NLABS-2 patterns.

INFRARED ASPECTS

Psychophysical principles were also applied in reaching the second objective; to provide the soldier with camouflage protection at night as well as during the day. Although principles followed in designing the visual characteristics of the Woodland pattern are rather well quantified, this is not the case for infrared parameters. The reason for emphasis on infrared signatures of potential targets lies in the capability of certain devices to "see" in the dark by using infrared radiation. Three questions must be addressed. How can the relevant infrared entities be quantitatively related to what is seen? How can the infrared standard values best be defined? What are the infrared tolerances? The following develops a general methodology for handling these questions.

General Background

At night, two sensors are major threats to personnel: thermal imagers and image intensifiers. The former respond to infrared radiation emitted by objects and terrains through the 3 to 5 μm and 7 to 14 μm windows of the atmosphere. Unless special measures are taken, soldiers can readily be distinguished from cooler backgrounds with these devices. State of the art, however, is not yet able to furnish these measures in a practical way. On the other hand, no fundamental or practical barriers now prevent attainment of camouflage objectives to meet the threat of image intensifiers.

The underlying principles of image intensification form the basis for a variety of field devices ranging from drivers' night goggles to low light level television systems. The unit used in this study was an AN/PVS-2B Night Vision Sight, modified to provide automatic brightness control. This device is typical of items referred to as starlight scopes.

Because available radiation from the night sky is sufficient for their operation, starlight scopes require no auxiliary light sources, differentiating them from "active" devices. Radiation from the sky is reflected by an object in the same manner as visible light and imaged on photosensitive surfaces that emit electrons roughly in proportion to the intensity of the radiation incident on the tube. The electrons are accelerated through a micro-channel plate in a number of stages in a manner similar to that in a photomultiplier tube. Ultimately, an avalanche of electrons reaches a phosphor plate where a visible image is produced. By this process, the intensity of the original image has been amplified by a factor in excess of 10,000. The photo surfaces used in current image intensifier tubes are sensitive to both visible and near-infrared energy, covering a spectral range from less than 400 nm to about 900 nm. References 11 and 12 describe some of the salient features of both second and third generation starlight scopes, which are similar but not identical to the first generation device used in this study.

Quantitative Methods

Reduction of contrast is the major objective of camouflage. It is the variations in contrast that constitute an image, including those seen in a starlight scope. These images appear as a greenish monotone of varying levels of brightness, which allows use of the conventional definition of contrast, C. Although the term "contrast" developed within visual science, this study uses the principles to interpret images in a starlight scope.

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$$C = (B - B_o)/B_o \quad (3)$$

B = brightness of an object and
B_o = brightness of the background

It is a purpose of this paper to describe general methods whereby the infrared factors that influence contrast seen in a starlight scope can be handled objectively. Three optical factors influence the variations in contrast one sees in these monotone images; spectral power distribution of the illumination, spectral sensitivity of the sensor, and spectral reflectance of the objects and terrains. Visual science relates similar factors for the eye in a quantitative manner to yield luminous reflectance, Y, a correlate of lightness, by the integration

$$Y = \int_{400}^{700} E_\lambda \; \bar{y}_\lambda \; R_\lambda \; d\lambda \quad (4)$$

where E_λ = spectral power distribution of a specified illuminant, usually daylight
$\bar{y}_\lambda$ = photopic sensitivity function for the eye and
R_λ = spectral reflectance factors for objects.

Although Y may be correlated with brightness, the correlation is not linear. In visual colorimetry, a linear psychometric scale that is often used is defined in CIELAB terms as

$$L = 116\,(Y/Y_n)^{1/3} - 16 \quad (5)$$

where Y_n = integrated reflectance of a perfect white.

Available illumination in a battlefield varies widely at night and includes both natural and man made sources. To illustrate the methodology we have chosen two of the more common and extreme natural types; moonlight and the radiance of a clear moonless night sky. These approximate the extremes in spectral power distribution one may expect in a battlefield environment. Moonlight is similar to well-characterized sunlight mediated by the reflectance of the moon and effects of the earth's atmosphere. For the purpose of this paper we consider the spectral power distribution of moonlight to be equivalent to CIE illuminant D5500. A more complex situation exists for defining the distribution of the moonless night sky and that within shadows on a moonlit night. Published data show this varies widely due to unpredictable photochemical reactions of the upper atmosphere which generate much of the radiation (11-16). Although differing in detail, the data agree that the night sky radiates far more infrared energy than visible light. The curve shown in Figure 6 for a moonless clear sky is one synthesized from the referenced data. To a variable and small but often significant degree, the spectral quality of the ambient light is influenced by the reflections from the ground. Because vegetation strongly reflects near-infrared radiation, illumination from the sky may be further enriched in the infrared than the figure suggests, when surrounds consist of shrubs, trees, and other foliated material.

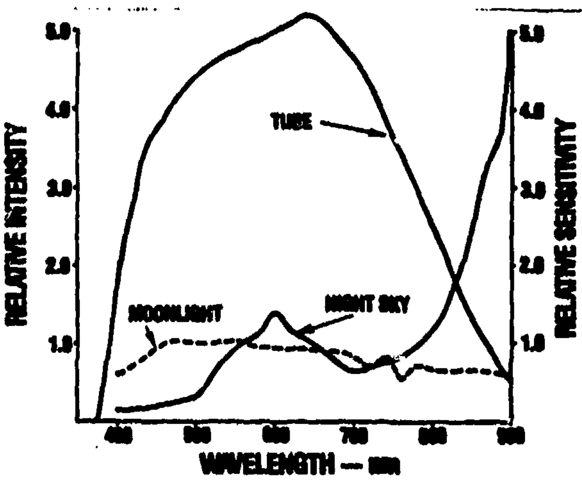

Figure 6. Selected spectral power distributions and the spectral sensitivity of a typical image intensifier.

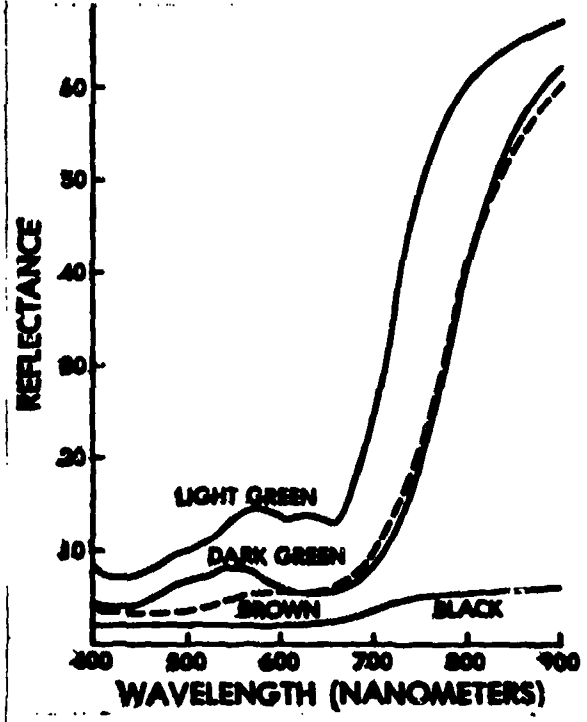

Figure 7. Spectral reflectance data for the Woodland pattern.

Among the many features of a starlight scope, its spectral sensitivity is of special interest to the researcher in camouflage. It is difficult to standardize on a particular set of values for this function for a number of reasons. Among these are variations in manufacture of a given tube type, variety of tube designs that actually are used, and influences of the optics of a given sensor design. Figure 6 shows a nominal sensitivity function for a typical second generation instrument (11, 12).

The third factor that determines contrasts in the image is the spectral reflectance of the objects represented in the image. An object that is characterized by a low reflectance curve is expected to appear darker in the image than one with a higher curve. This one factor over which a camouflage developer has some control is encumbered, however, by one constraint. Visual color requirements narrowly define the visible portion of the reflectance curves; only the infrared portion of the curve is a true variable for the researcher. Figure 7 shows reflectance curves of the four colors of the standard fabric for the Woodland pattern. Dyes were selected for printing the pattern to meet visual requirements and the infrared values derived from the method described in the next section.

Standard Values

The three factors of illumination, sensor, and object reflectance were related by integration in a manner analogous to that of Equation 4.

$$N_s = \int_{400}^{900} I_\lambda \; S_\lambda \; R_\lambda \; d\lambda \qquad (6)$$

where, to avoid confusion with the terminology of color science, Y is replaced by Ns, connoting nighttime illumination and the starlight scope and

I_λ = spectral power distribution of moonlight or the night sky radiance,

S_λ = spectral sensitivity of the sensor.

Table I summarizes integrations using Equations 4 and 6 for visual (daytime) and starlight scope images, respectively. Integrations for Y

Table 1. Integrated Reflectance and Lightness for Several Specimens for Visual and Starlight Scope Observation

Specimen	Daylight Y(L)	Moonlight Ns(Ls)	Night Sky Ns(Ls)
Woodland Pattern			
Light Green	12.1(41.3)	18.3(49.9)	23.0(55.1)
Dark Green	6.9(31.5)	10.1(38.0)	13.3(43.2)
Brown	4.8(26.0)	9.2(36.3)	12.9(42.6)
Black	2.3(16.8)	2.8(19.0)	3.0(20.0)
Merged Pattern	6.5(30.6)	10.3(38.4)	14.1(44.4)
Munsell Grays			
N-3	6.1(29.6)	5.9(29.2)	5.8(29.0)
N-4	12.2(41.5)	11.8(41.0)	11.6(40.6)
N-5	20.4(52.3)	19.8(51.6)	19.4(51.2)
N-6	29.2(61.0)	28.3(60.2)	27.8(59.7)
N-7	43.1(71.6)	41.8(70.7)	41.0(70.1)
N-8	59.7(81.7)	57.9(80.6)	56.8(80.0)
Olive Green 507	7.9(33.8)	8.1(34.2)	9.1(36.3)
Olive Green 107	7.3(32.6)	6.7(31.1)	7.8(33.5)
Maple Leaf	8.1(34.3)	12.0(41.2)	16.4(47.5)
Hedge Leaf	11.2(39.9)	14.5(44.9)	19.3(51.1)
Aspen, summer (17)	5.8(28.9)	9.9(37.6)	13.8(44.0)
Soil, plowed (17)	6.0(29.3)	7.4(32.6)	9.0(36.0)
Meadow, summer (17)	9.5(36.9)	13.6(43.6)	18.9(50.6)

were based on the 1931 CIE Standard Observer and Source D6500; for Ns, the data that form the basis of Figure 6 were used for both moonlight and night sky illumination. Specimens that were evaluated include the four colors of the Woodland pattern, relevant monotone clothing fabrics, a series of

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Munsell neutral gray samples, two leaves measured in the laboratory, and representative Krinov terrain data (17).

It is no more reasonable to expect that the contrasts observed visually in the image of a starlight scope are linearly related to the integrated reflectance values than they are for visual observation. In one attempt to explore possible linearity, values of Ns were converted to the lightness analog, Ls, using Equation 5. These data are also summarized in the table, in parentheses.

The following procedure was used to estimate optimum Ns or Ls values for the Woodland pattern to provide least contrast in a variety of temperate terrains at night. The Munsell gray scale identified in Table 1 was viewed through the starlight scope on both moonlit and moonless nights in a Massachusetts setting, a part of which is shown in Figure 8. Backgrounds consisted of miscellaneous brush up to eight feet in height and deciduous trees (primarily maple) up to 40 feet high. Observations were made both in early spring before leaves emerged and in the summer when foliage was in full bloom. N-3 was too dark under all conditions, except when placed directly in front of a dark shadow. The best matches to terrain elements such as tree trunks, twigs, and leaves were found for N-4 and N-5. N-6, N-7 and N-8 usually were conspicuously light.

Figure 8 is a photograph of three manikins taken at a distance of about 50 m on a moonless night in the setting described above. The Woodland patterned uniform is flanked by the durable press monotone OG-507 fatigues on the right and the NLABS-1 patterned uniform used in Vietnam on the left. Figure 8 clearly shows that, for the given scene on a moonless

Figure 8. Photograph taken through a starlight scope on a moonless night against a background of miscellaneous shrubs and tree. The three uniforms are, left to right, NLABS-1, the Woodland pattern, and the durable press OG-507. The dimness at the edges of the scene is an aberation of the photography.

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Figure 9. Close up view of Woodland pattern showing three-level pattern seen through starlight scope.

night, the Woodland pattern is superior to the two uniforms it is replacing. Numerous observations were made in both deciduous and coniferous surrounds, in every season of the year, on moonless and moonlit nights, both clear and overcast. In every case the Woodland pattern showed less contrast with the backgrounds than the other two uniforms.

It was intended that the Woodland pattern should appear as a pattern when viewed with a starlight scope at night as it does visually in the day. Figure 8, the data of Table 1, and the personal observations confirm that the brown and dark green areas of the pattern are usually difficult to differentiate. What is seen, however, are three distinct levels of lightness that produce a three-level pattern, as shown in Figure 9. As in daylight, the black areas resemble shadows; the other areas resemble other commonly found terrain components. While the data of Table 1 are sparse, many night observations under a variety of conditions support the decisions that constitute the basis of specification requirements for procurement.

Allowable Tolerances

For the visual characteristics of the pattern, a series of textile samples have been selected to guide the inspectors in judging visual acceptability for each color. Because the uniform is worn in garrison as well as in the field, esthetic factors require the visual tolerances to be a bit tighter than they would be, if only combat conditions were considered. For the four colors of the Woodland pattern, the present tolerance ranges average about two CIELAB color difference units; somewhat less in hue, somewhat more in lightness. Both end-item purpose and the ability of the textile industry to produce large quantities of material were taken

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into account in establishing these tolerances.

It is essential that research also provide guidance to procurement on the range of variations in infrared reflectance that is acceptable. An effort to meet this need is being performed on two levels; one to provide immediate guidance to procurement, the other is a longer range effort to give a more fundamental basis for establishing the range. For the infrared aspects of the ~~tolerances, only camouflage effectiveness~~ and industry capability need to be considered.

To meet the immediate ~~needs of procurement~~, the current specifications define acceptability in ~~terms of a range of spectral~~ reflectance factors at each wavelength in the ~~infrared taken~~ at 20 nm intervals. The weakness of this procedure lies in its failure to take account of the integrating operation of a starlight scope as expressed in Equation 6. A reflectance factor ~~at one wavelength that is too low may be compensated by one or more higher values at other wavelengths. The method~~ described below overcomes that weakness in the current method of inspection. Moreover, since the data derive from commercially produced visual tolerances, they illustrate the present industrial ability to control the infrared as well as visual characteristics.

Reflectance factors were measured from 400 to 900 nm for the visual tolerance samples for each of the three major colors and integrated by Equation 6. For the black area of the pattern, no lower limit is needed. Table 2 summarizes the ranges found for the three colors for Ns and Ls.

Table 2. Range of Ns and Ls for the Three Major Colors of the Woodland Pattern for two Night Illuminations.

	Moonlit Night		Moonless Night	
	Ns	Ls	Ns	Ls
Dark Green	8.0 to 10.1	(34.1 to 38.0)	11.0 to 13.2	(39.5 to 43.2)
Light Green	15.2 to 18.2	(45.8 to 49.7)	18.5 to 23.2	(50.1 to 55.3)
Brown	7.6 to 10.0	(33.0 to 37.9)	11.2 to 14.4	(40.0 to 44.9)

The ranges shown in Table 2 fall within the range of values shown in Table 1 for typical terrain elements. Taken with the black area, the data show that a three-level pattern will still be seen as long as reflectances remain within the ranges shown in Table 2. It was stated above that the dark green and brown areas were difficult to differentiate through a starlight scope. Table 2 shows acceptable variations in Ns for both areas are much larger than differences between the two areas in the standard. It may also be noted that, for reasons of color durability in use, the values for the standard lie near the upper limit of the tolerance ranges.

The above shows that the level of industrial control exercised in

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production of the Woodland pattern has been adequate to meet the infrared aspects of the objectives. These results, however, do not provide a total basis for establishing tolerance criteria for other applications, for example, a desert uniform. A general method must also consider the responses of the electro-optical device at various levels of illumination and its interaction with the eye of the observer. We have observed that the contrast threshold increases and resolution decreases as the light level falls. It remains to be determined quantitatively how instrument performance over a variety of conditions influence the criteria needed to produce satisfactory camouflage materials. This is part of the current research.

SUMMARY

Psychophysical principles were applied to several aspects in both the design and production of the recently adopted Woodland patterned Battle-Dress Uniform. These principles pertain to both visual and the near-infrared characteristics of the pattern.

- Well-known methods were applied to select each of the standard colors of the pattern and to define permitted variations in production.

- A little-known technique was modified to predict maximum visual range of effectiveness and to guide in final selection of colors.

- Basic principles of human vision were adapted to guide infrared aspects of the Woodland pattern. These relate to nighttime detectability by the starlight scope/eye interaction. The new methods were used to define both standard values and allowable variations.

These principles and the supporting dye formulation studies reported in Reference 5 have made possible the large scale production of acceptable fabrics. About 2,500,000 Battle Dress uniforms have now been procured. These provide troops with far better camouflage protection, both day and night, than they received in the past.

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