Color Vision in Color Display Night Vision Goggles

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INTRODUCTION: Aircrew viewing eyepiece-injected symbology on color display night vision goggles (CDNVGs) are performing a visual task involving color under highly unnatural viewing conditions. Their performance in discriminating different colors and responding to color cues is unknown.

METHODS: Experimental laboratory measurements of 1) color discrimination and 2) visual search performance are reported under adaptation conditions representative of a CDNVG. Color discrimination was measured using a two-alternative forced choice (2AFC) paradigm that probes color space uniformly around a white point. Search times in the presence of different degrees of clutter (distractors in the scene) are measured for different potential symbology colors.

RESULTS: The discrimination data support previous data suggesting that discrimination is best for colors close to the adapting point in color space (P43 phosphor in this case). There were highly significant effects of background adaptation (white or green) and test color. The search time data show that saturated colors with the greatest chromatic contrast with respect to the background lead to the shortest search times, associated with the greatest saliency. Search times for the green background were around 150 ms longer than for the white. Desaturated colors, along with those close to a typical CDNVG display phosphor in color space, should be avoided by CDNVG designers if the greatest conspicuity of symbology is desired.

DISCUSSION: The results can be used by CDNVG symbology designers to optimize aircrew performance subject to wider constraints arising from the way color is used in the existing conventional cockpit instruments and displays.

KEYWORDS: visual adaptation, color adaptation, visual performance.

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The aim of the work reported here was to understand the performance limitation of the human color vision system in observers who are adapted to green night vision devices (NVDs) such as those used by aircrew as well as other military personnel, hunters, etc. The question is of particular relevance to emerging NVDs that use color symbology injected at the eyepiece and overlaid onto the monochrome output of an image intensifier. Such devices are currently termed color display night vision goggles (CDNVGs) to distinguish them from the previous generation of display night vision goggles, in which symbology was injected at the objective lens, passing through the image intensifier tube to appear to the wearer as a monochrome overlay on the night vision scene.

CDNVGs offer the potential of presenting information to aircrew flying at night that, by the use of color coding, may be seen more rapidly and be more conspicuous against the monochrome night vision scene background. The use of color also offers an additional perceptual dimension that could facilitate richer information coding and presentation to aircrew. Color is already used in existing cockpit instruments to delineate, for example, acceptable ranges of aircraft or flight parameters; this delineation could be extended to the view through NVDs. Torque could, for instance, be displayed in an accepted neutral color when in its normal operating range and in red when outside that range.

Those designing symbology sets for CDNVGs need an awareness of how their choice of color will be perceived by wearers of the devices and how those choices could, in turn, affect aircrew performance. The research reported here gives guidance in terms of colors which elicit good and poor performance under the adaptation condition present when viewing NVDs. Performance is reported in terms of the ability of observers to discriminate between different hues, reaction times in searching for—and

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correctly identifying—a color-coded target in a cluttered scene, and accuracy in the search task.

The human visual system is remarkable in its use of adaptation to maintain adequate visual performance in a wide range of visual environments. Light and dark adaptation have been characterized, both in terms of their time course, spatial characteristics, and absolute sensitivity.[1,9,10] Chromatic adaptation has also been studied extensively and data on color discrimination, color appearance, and temporal characteristics of chromatic adaptation phenomena have all been reported.[11,14,16]

Aspects of human color vision under different chromatic adaptation conditions have been studied previously. Pointer[24] reported that just noticeable differences decreased in areas of color space close to the chromaticity of the adapting background; in other words, color discrimination improved when the colors being tested were similar to the background. This was found to be true for red, green, and blue adapting fields and also for a range of 'white light' adaptation conditions. In an earlier experiment Hurvich and Jameson[11] reported that wavelength discrimination improved in the parts of the spectrum closest to the adapting field. Loomis and Berger[18] showed that wavelength discrimination and color appearance followed a similar pattern, a result which is reminiscent of luminance adaptation effects described by Craik.[5] More recently Jennings and Barbur[13] demonstrated 'Weber-like' results for small perturbations away from a range of background colors when both background and test stimuli were described in terms of long-, medium-, and short-wavelength sensitive retinal cone classes. In both color and luminance domains, experimental evidence points to the human visual system performing best at detecting small variations from a background to which it has adapted, and performing less well when background and stimulus are separated to a larger degree in the relevant parameter space. Thus, in terms of color, we might reasonably expect color discrimination to perform best (i.e., be capable of detecting very small changes in color) when tested using colors that are similar to the background, and to perform poorly when tested using colors that are very different from the background.

Rinner and Gegenfurtner[26] examined the time course of adaptation with respect to both color appearance and discrimination. The authors concluded that chromatic adaptation for discriminating changes in background color was thought to be retinal in origin, but adaptation affecting color appearance showed an additional, faster adaptive change that seemed to be cortical in origin. The research reported in this paper builds upon the aims of these earlier studies, but removes changes in saturation from the color discrimination paradigm, adding a visual search component that is judged to be relevant to the role played by colored symbology in a CDNVG.

METHODS

Subjects

The experimental studies reported here adhered to the principles of the Declaration of Helsinki. Written informed consent was obtained from all subjects prior to participation in the experiments, which were conducted in accordance with a protocol approved by an independent human research ethics committee. All subjects were volunteers and received no payment for taking part in the study. The study was funded by the UK Ministry of Defense.

Two experiments were conducted in the laboratory: Experiment 1 measured hue discrimination and Experiment 2 measured visual search performance. Seven male subjects and four female subjects participated in Experiment 1. One of the subjects was unable to participate in Experiment 2 for reasons unrelated to the study. Provided participants are screened for X-linked color vision defects (see below), there is no evidence for color vision differences between the sexes.[6] Subjects were between 18 and 55 yr of age. Normal trichromatic color vision was confirmed in each subject using the Type 1 Nagel Anomaloscope (Schmidt and Haensch GmbH, Berlin, Germany). All had corrected Snellen visual acuity of 6/6.

Experimental Design

Hue discrimination (Experiment 1) was measured under controlled laboratory conditions using a spatial two alternative forced choice (2AFC) paradigm with multiple interleaved adaptive staircases. The task was designed with temporal parameters that favor the color-sensitive mechanisms of the human visual system over the luminance mechanism.[21]

In Experiment 1, subjects were shown two pairs of colored discs on a computer monitor, on either side of a central fixation point. On each trial presentation one pair of discs was identical in color and one pair different, with the color difference defined by an adaptive staircase described below. Occasional presentations, selected on a random basis, had a large and very obvious color difference between the discs in one of the pairs to motivate subjects to continue responding. Subjects were asked to indicate, using a response box, which pair of discs—left or right—differed in color. The task has spatial properties similar to that used by Krauskopf and Gegenfurtner,[16] but with different temporal properties and spatial parameters; in the current experiment the colored discs subtended a visual angle of 1.2° at the observer distance of 1 m and were presented so that the center of each disc was at an eccentricity of 2.6° relative to the fixation spot. An adapting green or white background field filled the monitor screen, which subtended a visual angle of $22.9° \times 17.2°$. The green adapting background was a metamer of the P43 phosphor commonly found in NVD image intensifier tubes. The background had a measured luminance of $10.0 \text{ cd} \cdot \text{m}^{-2}$ and a chromaticity of $u' = 0.1478$, $v' = 0.5564$. The luminance of the colored discs and green and white backgrounds was maintained at a constant $10 \text{ cd} \cdot \text{m}^{-2}$. The intrusion of luminance artifacts was reduced by conducting heterochromatic flicker photometry along each of the eight color directions used in the trial.

Adaptive staircases were used in the experiment, based on a transformed up-down method.[17] This approach is appropriate for the estimation of hue discrimination thresholds in preference to other, more sophisticated and efficient adaptive techniques such as PEST or QUEST in which there is an underlying assumption that stimuli are equally spaced in logarithmic space.[29,30] For tasks such as hue discrimination that assumption is not valid and, therefore, adaptive staircases must use the slightly less efficient up-down rules. In the current experiment a one-up, three-down rule was used,[17] which for a 2AFC design estimates the 75% point on an underlying psychometric function. The rule means, in this context, that hue difference between the disks is increased after one incorrect response and decreased after three correct responses. Statistical independence of successive trials in the staircase was ensured by interleaving multiple staircases during each session.

In order to map color space to a useful degree, subjects were asked to judge hue differences in different directions in a standard Uniform Color Space (UCS) defined by the Commission Internationale de l'Eclairage (CIE) and known as 1976 UCS (**Fig. 1A**). This space was chosen because it is recognized as being approximately perceptually uniform.[25] The system also has the advantage that coordinates in 1976 UCS can be back-transformed to CIE 1931 chromaticity (x, y) for discussions with CDNVG manufacturers, who are usually more familiar with that colorimetric system. Eight directions in color space were measured in the trials, in both 'white' and 'green' background conditions (Fig. 1A). Hue angle is specified relative to a line of constant v′ originating at the white point and going to the right-hand side of Fig. 1A. Directions 354.6°, 91.3°, 174.6°, and 271.3° correspond to the Cardinal Axes established by Derrington, Krauskopf, and Lennie.[5] The Cardinal Axes arguably represent the underlying principal components of post-receptoral human color vision; one corresponding to a 'red-green' direction in color space and the other to a 'yellow-blue' direction. Four intermediate directions were added for the current study to give extra information on the areas of color space that lie between the two Cardinal Axes.

In each trial, except for blanks, the hue of one of the four discs chosen at random was changed by an amount determined by the adaptive staircase algorithm. The stimulus set provided to each staircase at the start of the experiment consisted of 40 values equally spaced in UCS (i.e., u', v') and defined in polar coordinates at constant radius $r = 0.05$ from the monitor white point (**Fig. 2**). Radial distance in UCS corresponds to saturation of color, with white at the center and completely saturated, or purest, spectral colors at the largest r values. Thus saturation and luminance were kept constant while hue changed.

The aim of Experiment 2 was to measure saliency of colored targets in the presence of a number of distractors. Salient or highly conspicuous objects in a scene can be strong cues for observers and typically reduce visual search times.[12] The presence of salient objects may even stimulate pre-attentive mechanisms, leading to so-called 'pop-out,'[28] which is discussed in more detail below. Measurements of human performance were made when subjects were adapted to the same 'green screen' CDNVG simulation as Experiment 1 and when they were adapted to a neutral white as a performance baseline. Salience, or 'pop-out' due to color was measured using a variant of a paradigm originated by Treisman[27,28] and subsequently developed by Itti and Koch[12] in a discussion of saliency.

The technique measures different aspects of observer performance (such as search time for a specific target, or accuracy in detecting a target shape among distractors) when the parameters of the target or distractors are changed. The original authors varied target orientation, color, contrast, and size. In the experiments described here, only color of the target was varied systematically; target size and luminance contrast were

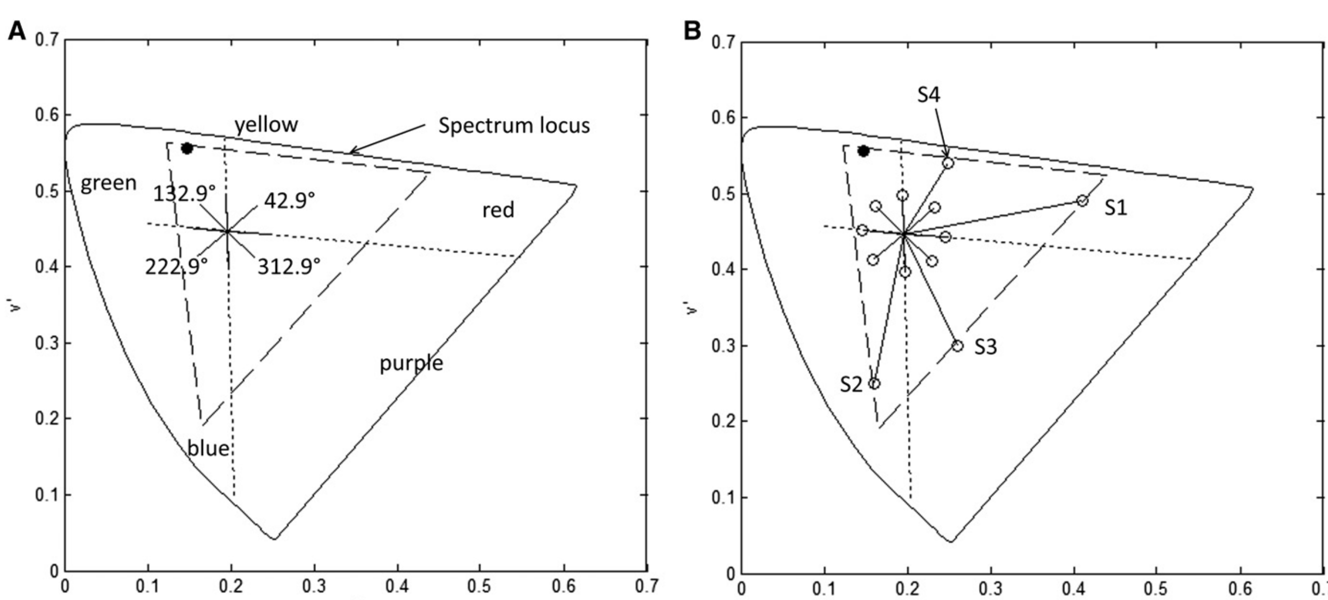

Fig. 1. A) CIE 1976 UCS showing the eight color directions measured in Experiment 1 ('star' shape; alternate directions labeled with their hue angles). Black dotted lines are the Cardinal Axes of Derrington, Krauskopf & Lennie;[7] long dashed lines represent the limits imposed by the monitor gamut. The black circle in the upper left of the diagram is the position in this color space of the P43 phosphor used in most NVG tubes. B) The 12 colors used in the visual search trials (Experiment 2).

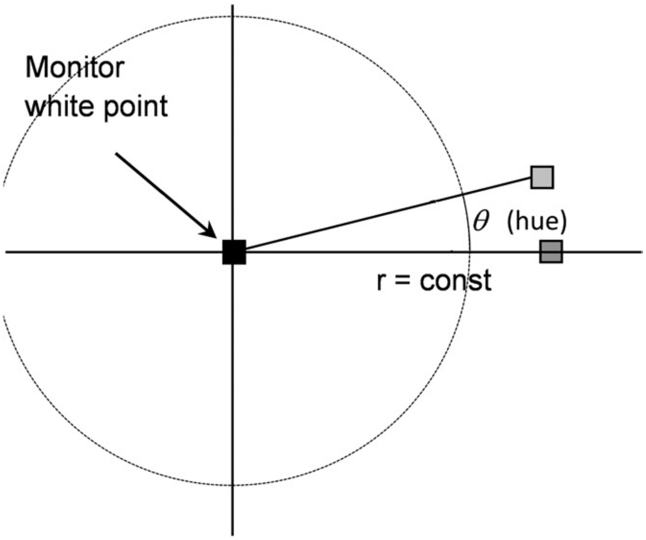

Fig. 2. Stimulus definition in CIE 1976 UCS. Stimuli were defined in terms of hue angle θ, radius r (which corresponds to saturation), and luminance L.

kept constant and the location and orientation of target and distractor shapes was randomized. Performance was measured for a single target in a field of 5, 10, or 15 distractors. Individual targets and distractors were bars subtending a visual angle of 0.5° × 0.15° at the viewing distance of 0.75 m. Subjects responded to the question, "Are the objects all the same, or is there an odd one out?" During Experiment 2, contrast of the distractors with respect to the background was maintained at a constant value and the target was varied in color across the different experimental conditions. During both white (baseline) and 'green screen' (NVD) conditions the distractors were white. If the NVD condition distractors were the same color as the green background, the task simply becomes one of chromatic contrast discrimination (i.e., observers would make their judgement based on the color difference between target and green distractors, which would be much greater than the target/distractor difference in the white condition). The experimental design avoided this situation by the use of white distractors throughout.

The following factors were varied:

- Target hue;
- Background/adapting field (either white or NVG green);
- Number of distractors present; and
- Target present/absent (i.e., some presentations had only distractors on screen, to measure the time taken for observers to decide that a target of a given, pre-cued color was not present).

In addition to the eight constant-saturation hues that were used in Experiment 1, four highly saturated colors S1 to S4 (**Fig. 1B**) were used in Experiment 2 to benchmark conspicuity for highly saturated colors likely to be used in CDNVG systems. The choice of saturated colors was informed by both the organic light-emitting diode display technology likely to be found in a CDNVG and the limitations imposed by the experimental monitor gamut. The resulting 12 hues (8 constant saturation and 4 highly saturated) are shown in Fig. 1B. They were coded as color indices from 1 to 12 for the purposes of data analysis.

The luminance of both adapting field and target in Experiment 2 was 11.8 cd · m^{-2}, based on the estimated mean luminance of a night vision device viewing a scene under starlight to quarter moonlight illuminance.[20] The luminance of the distractors was 14.75 cd · m^{-2} to provide positive contrast representative of typical symbology and give an appropriate level of difficulty in the task. Spatially random luminance noise was combined with the target/distractor stimuli and interleaved on a frame-by-frame basis in order to reduce luminance intrusion in the chromatic search task.

Procedure

For Experiment 1 (hue discrimination) subjects viewed a cathode ray tube (CRT) monitor in the laboratory upon which baffles were deployed to ensure that there were no screen reflections from ambient lighting. Subjects sat 0.75 m from the CRT and viewed the display binocularly.

Subjects took part in two sessions that were undertaken at different times. During one session, subjects adapted to the 10 cd · m^{-2} green P43 metamer background. During the other session, subjects adapted to a 10 cd · m^{-2} white background with chromaticity corresponding to the monitor white point (u′ = 0.1963, v′ = 0.4469) based on spectroradiometric measurements of the monitor screen. The order of green and white background sessions was randomized across subjects.

In all cases the stimuli were presented with a raised cosine temporal profile to favor the parvocellular pathway[21] and for a limited time. The time limitation controls the information available to observers in making the discrimination judgement and also avoids the apparent fading of peripheral objects over several seconds during steady fixation.[1,3] Stimuli were presented for 2.5 s, including a 0.5-s onset and 0.5-s decay. Subjects adapted to the green or white background for 2 min prior to the first stimulus presentation and 5 s between subsequent successive trials. They were instructed to maintain fixation on the central fixation cross at all times.

For Experiment 2 (visual search performance), two measures of performance were recorded: search time and accuracy. Subjects' search times and their accuracy in performing the task were measured using slightly different approaches, with the main difference being that stimuli were presented for 300 ms when measuring task accuracy, but were left displayed on the monitor until the subject responded when measuring search times. Following the 300-ms task accuracy presentations, subjects could respond at any time and both trials were thus self-paced. Accuracy was measured as correct or incorrect identification of the target presence or absence. Both trials were conducted during a single visit to the laboratory and the order in which subjects undertook the two variants was randomized across the subject pool, as was the order of green and white adapting conditions. Within each session the order of colors tested was also randomized to avoid learning effects. Prior to each test color, however, subjects were shown a small patch of the color, since this knowledge would be present in cockpit use of CDNVGs by aircrew.

Equipment

In Experiment 1, stimuli were presented on a Dell P1130 Trinitron CRT monitor (Dell, Round Rock, TX) and were generated using a Cambridge Research Systems (Rochester, Kent, UK) ViSaGe visual stimulus generator. Code to control stimulus presentation and record subject responses was written in Matlab® using the Cambridge Reseearch Systems toolbox for the ViSaGe. The monitor and ViSaGe were calibrated prior to the experiments and validation measurements were performed on the displayed stimuli using a spectroradiometer (PR-650, Photo Research, Chatsworth, CA). Adapting field luminance was confirmed using a calibrated photometer (LMT L1009, LMT Lichtmesstechnik, Berlin, Germany). Responses were recorded via a Cedrus RBX30 response box (Cedrus Corporation, San Pedro, CA).

For Experiment 2, software to display the stimuli was written in Matlab® using the Psychophysics Toolbox extensions.[2,15,23] Stimuli were displayed on a liquid crystal display monitor (SpectraView® Reference 241, NEC Corporation, Tokyo, Japan) calibrated using a Photo Research PR-650 spectroradiometer, the results of which were accessed by the software using the Matlab calibration structure in Psychtoolbox.[2] As in Experiment 1, additional verification measurements were carried out (PR-650) to confirm that the screen was displaying the chromaticity and luminance values being demanded by the software.

Statistical Analysis

Data were analyzed using multifactorial analysis of variance (ANOVA, Matlab® Statistics Toolbox) with fixed and random factors as reported along with results below. Subjects were their own controls since all subjects undertook baseline and 'green screen' trials as part of the study. Fixed factors in the ANOVA for Experiment 1 were background adaptation condition (green or white) and hue direction (354.6° to 312.9°; eight directions); subject number was included as a random factor. Fixed factors in the ANOVA for Experiment 2 were background adaptation condition (green or white), color index (1 to 12), and number of distractors (5, 10, or 15); subject number was included as a random factor.

RESULTS

Mean hue discrimination thresholds for all subjects from Experiment 1 are shown in **Fig. 3A**. Results are expressed as increment thresholds, i.e., the angle of the subject's threshold vector in UCS, θ, relative to the baseline direction for each of the eight hue directions tested (Fig. 2). Larger increment thresholds represent poorer color discrimination. Hue discrimination thresholds were higher in the green adapted condition than the white, but the differences between green- and white-adapted thresholds varied with hue angle, with the greatest differences around hue axes 354.6° and 174.6° (Fig. 1A). The results were confirmed by multifactorial ANOVA, which indicated highly significant effects of background adaptation [$F(1,160) = 160.32$; MSE = 0.00298; $P < 0.001$], hue direction [$F(7,160) = 16.47$; $P < 0.001$], and a highly significant interaction between background adaptation and hue direction [$F(7,160) = 6.45$; $P < 0.001$].

Mean search times for the green NVG and white baseline condition from Experiment 2 are shown in **Fig. 3B** for all distractor numbers and for stimulus presentations where the target was present. Corresponding data for 'target absent' are not shown, but the target absent situation is addressed in terms of search times, plotted as a function of the number of distractors (**Fig. 4**). Only correct responses were included in the analysis.

Multifactorial ANOVA conducted on the results showed highly significant effects of both color index ($P < 0.001$) and the number of distractors present ($P < 0.01$). The background adaptation condition was not significant in this experiment ($P = 0.256$), which was attributed to the presence of both increases and decreases in search time between green and white backgrounds across the range of color indices (Fig. 3B), although there is a tendency toward longer search times for the green adapted condition in 11 of the 12 color indices. There were no statistically significant interactions.

The experimental data are plotted for the green and white baseline conditions in Fig. 4.

Accuracy of subjects performing the search task was calculated using the sensitivity metric[8,19] d'. Use of the d' metric eliminates the effect of the internal criterion of observers by taking into account their false alarm rate in addition to the measurement of success in the task (commonly termed 'hit rate'). The data showed marked differences across the range of color indices studied. There was no single trend for the green/white background difference in terms of d'; for a large subset of hue directions, observers showed greater sensitivity in the white background task than its green background counterpart, while for a smaller subset (directions 174.6° and 271.3°), observers were more sensitive in the green background task than the white.

DISCUSSION

Hue discrimination in normal trichromatic human observers is understood to be mediated by two orthogonal color-opponent mechanisms, which may broadly be termed 'red-green' and 'blue-yellow'. The visual system shows considerable resilience to changes in illuminant color. For example, humans viewing colored objects under a colored illuminant perform surprisingly well in judging color differences under such seemingly contrived conditions. However, adapting the visual system to a strongly colored light source—as happens when aircrew use NVDs for prolonged periods—and its response to colors is an area that is less well understood. Specifically, for aircrew adapted to the 'green screen' world of the CDNVG, the use of a

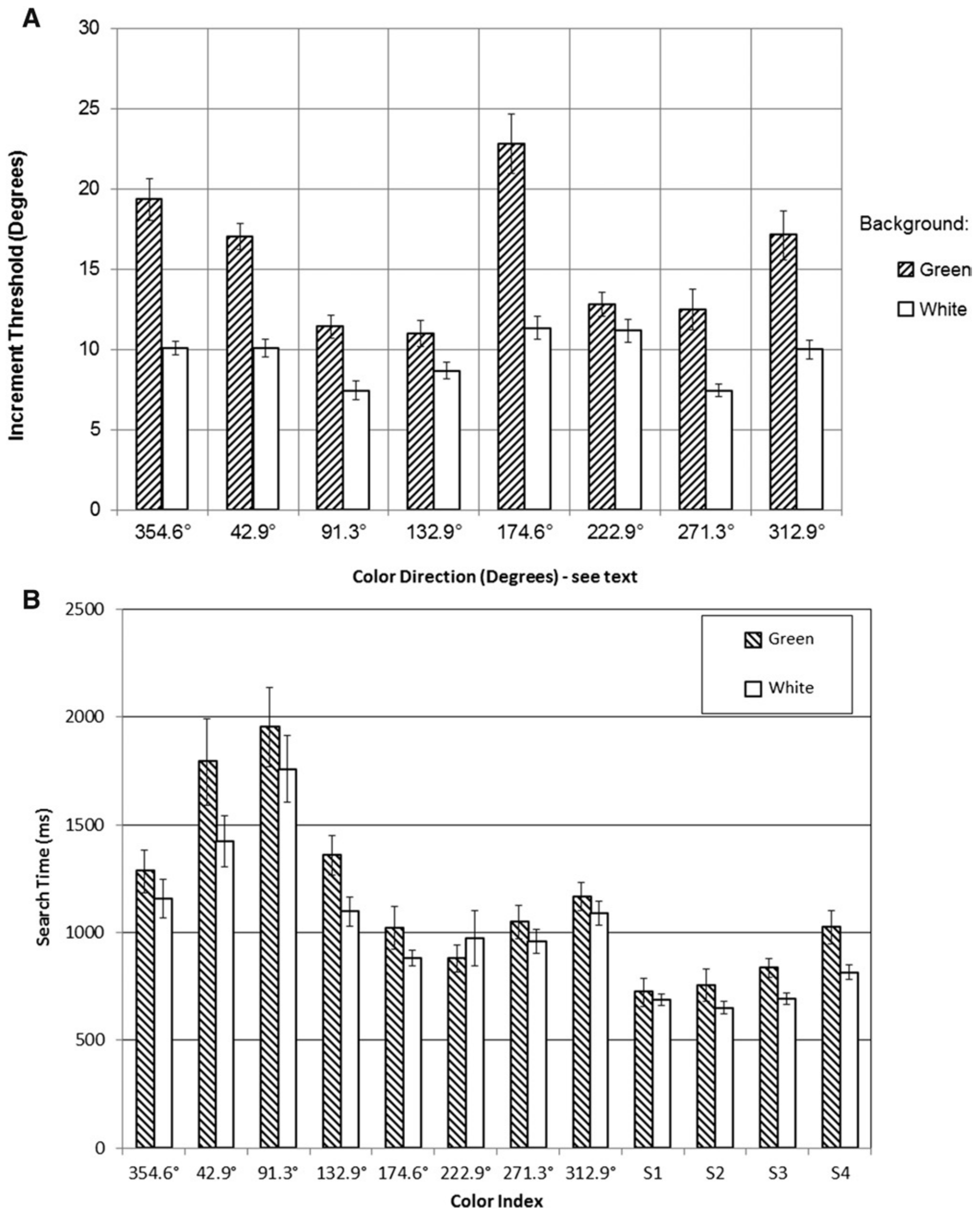

Fig. 3. A) Mean hue discrimination thresholds ($N = 11$) under 10 cd · m^{-2} NVG green display adaptation and a comparable white baseline adaptation. B) Mean search times ($N = 10$) for 'target present'. Color index is shown as the angle in UCS, as in Experiment 1, for the first eight colors. However, the addition of 4 saturated colors in Experiment 2 (S1 to S4) gives a total of 12 color indices on the abscissa. S1 is a highly saturated red, S2 is a highly saturated blue, S3 represents a purple that lies at a point in color space diametrically opposite to the P43 phosphor, and S4 is a saturated yellow. Error bars show ± 1 SEM.

conventional symbology set superimposed on the scene needs careful consideration. The results of the two experiments reported here provide helpful data to system designers which are considered in two different contexts: how well subjects discriminate between closely related colors (Experiment 1) and how conspicuous various colors are when subjects are adapted to the NVD display, measured in terms of either search time or accuracy in performing a visual search task (Experiment 2).

The results of Experiment 1 indicate that hue discrimination is poorer when subjects are adapted to a green background, and that the effect is present at all of the points sampled in color space. The impact of adapting to the green background is much stronger around the Cardinal Axis, running approximately green-to-red (directions 354.6° and 174.6°, Fig. 1A), a result which, at first glance, appears simply to confirm the selective habituation reported by Derrington, Krauskopf and Lennie in deriving their 'Cardinal Axes.'[7] Those authors noted that responses to modulation along one of the Cardinal Axes were reduced when subjects viewed an adapting field that lay along the same direction away from the white point, but that adaptation to colors on the orthogonal axis produced no change in sensitivity. The 'green screen' seems to impact discrimination along the red-green axis. However, the stimulus configuration employed here reveals a more complex interrelationship.

Hue directions 354.6° and 174.6° (Fig. 1) do indeed lie along an axis that can be described as 'red-to-green', but the experiment reported here measures discrimination along a color vector that is, for small values of θ in Fig. 2, perpendicular to that axis. In other words, hue discrimination in directions 354.6° and 174.6° is really measuring discrimination in a direction that could be described as blue-to-yellow. Noting now that the P43 phosphor simulated in these experiments represents a considerable yellow shift, relative to the white point (Fig. 1), the impact of P43 adaptation on blue-to-yellow color discrimination becomes less surprising. The 'green screen' is something of a misnomer and, in objective terms, the large effect on hue directions 354.6° and 174.6° makes a good deal of sense.

Similarly, the much smaller increase in discrimination threshold for hue directions 132.9° and 222.9° (Fig. 3A) can be understood by considering the fact that the P43 phosphor represents a much smaller vector shift, relative to the white point, in the directions tested in color space—but a nonzero shift nonetheless, leading to a measurable effect on hue discrimination for directions around 91.3° and 271.3° (Fig. 1A).

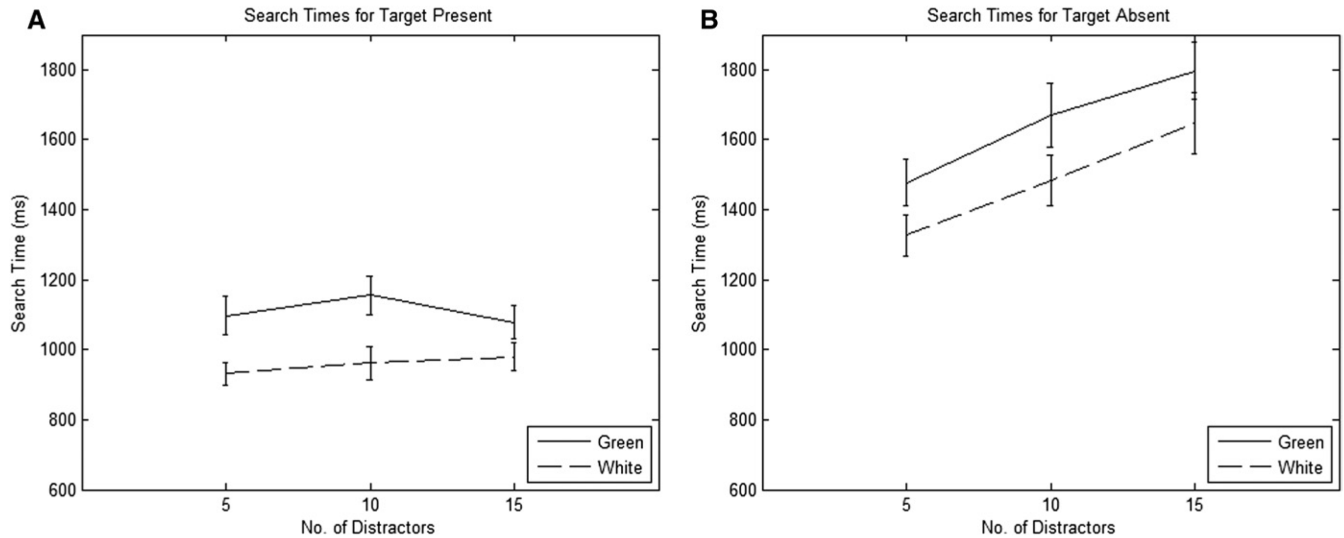

Fig. 4. Reaction times plotted against number of distractors when A) the target is present and B) when the target is absent for green and white adaptation. Error bars show ± 1 SEM.

In comparison with the earlier data of Hurvich & Jameson,[11] Pointer[24] and Loomis and Berger[18] show some similarities, along with some differences that can be attributed to the different experimental methods used. Some authors have limited their investigations to small deviations away from the background color,[13,24] while others measured color discrimination at points that were well-separated from the background in color space.[11,18] The previous data suggest that the human visual system responds to colored adaptation by optimizing performance close to the position of the adapting light in color space. In our experiment this would be represented by hue directions 91.3° and 132.9° (Fig. 1A). The results of Experiment 1 do indeed show the smallest discrimination thresholds under the green adaptation condition in hue directions 91.3° and 132.9° (Fig. 3A), although we did not see an improvement relative to the white-adapted condition in this specific discrimination task.

The method reported here differs in a number of important respects from the previously reported studies. Firstly, saturation was ignored by subjects in the present experiment and, secondly, discrimination was measured using a 2AFC trial design as opposed to the method of adjustment, offering advantages in terms of controlling bias. Thirdly, we have concentrated on discrimination close to the white point, with the overall aim of a systematic exploration of color space.

The search time data from Experiment 2 for green-adapted and baseline (white) conditions show the relative advantages of different areas of color space under the two adaptations. Colors close to hue directions 222.9° and S1 led to shorter mean search times in the green-adapted condition when the target was present, or to times that were not discernibly worse than the baseline white condition (Fig. 3B). Colors in directions 42.9°, 91.3°, 132.9°, and S4 performed poorly. The overall story appears to be the opposite of that told by the discrimination data. For lower search time, colors furthest away from the adapting point on the chromaticity diagram are advantageous. These colors are likely to have the greatest saliency against the green background due to their higher chromatic contrast, bearing in mind that luminance differences with respect to the background were not present as cues. It can be noted in passing that the saturated colors used in Experiment 2 all led to shorter search times than the desaturated subset.

In terms of the search data (Fig. 4), flat functions indicate the presence of so-called 'pop-out', where search time is independent of the number of distractors present[22,28] and it is reasonable to assume that the dimension facilitating pop-out in these trials is color with respect to the distractors. The flat search functions for both green and white backgrounds when the target is present show that 'pop-out' is present in both conditions. There is, however, one consistent difference between the green adapted condition and the white background: search times are longer (by approximately 150 ms) for the green adapted condition no matter how few—or how many—distractors are present. The 'target absent' data are unsurprising (Fig. 4B); the absence of pop-out is the only possible result, given that there is no target, and subjects take longer to judge that the target is absent when there are more distractors. Nevertheless, the 'target absent' data are interesting in that they show the same, consistently longer search times in the green screen condition, implying that the visual search task is more demanding when attempted against the green background. Again, the offset in search time is approximately 150 ms.

The key findings of the study are 1) there is no fundamental reason why color should not be used in DNVGs; 2) different colors give rise to different levels of human performance—the differences in human performance for different colors emerge clearly in the color discrimination, reaction time, observer sensitivity (d'), and percent correct data; 3) the green screen makes color discrimination performance worse and some areas of color space are more severely impacted than others; and 4) the green screen increases reaction time in searching for a target among clutter when the target is present, but has no effect on the time taken to reach a correct decision that there is no target.

It is recommended that 1) color is used to draw attention to important information, but telling colors apart should not be employed for information that is essential for safe flight or operational effectiveness; 2) if it is unavoidable that aircrew need to discriminate between different colors, those should be well separated in color space; 3) saturated red, blue, and violet have good salience or 'pop-out' when information needs to stand out from a cluttered green NVG background; and 4) choice of colors needs to be made such that there is no avoidable conflict with color conventions already in use in conventional cockpit instruments and displays.

The limitations of this study are as follows: The experiments reported here have only addressed a specific display luminance ($10\ \text{cd} \cdot \text{m}^{-2}$ in Experiment 1; $11.8\ \text{cd} \cdot \text{m}^{-2}$ in Experiment 2) corresponding to the mean luminance of a CDNVG device viewing a scene under starlight to quarter moonlight illuminance. The results could be different at other scene illuminances, particularly at very low illuminance levels outside the cockpit when areas of the CDNVG display may be in the mesopic region. The data presented are only valid for the P43 display phosphor; different phosphors could give different preferred colors. Adaptation of aircrew to P43 phosphor could impact the CIE signal light definitions[4] and further work is required to establish the need for any modifications and to define those modifications.

The two experiments reported here characterize two aspects of color vision under adaptation conditions experienced by aircrew wearing CDNVGs. The color discrimination data from Experiment 1 illustrate how color vision responds at a fundamental level, with discrimination being optimized for colors closest to the P43 phosphor chromaticity. For systems designers, it is probably less critical that CDNVG users can discriminate closely related colors in display symbology and, thus, these data are more helpful in developing an understanding of how the human visual system adapts to optimize color vision in unnatural visual environments.

The search time data are of more applied relevance and indicate that, in the absence of luminance contrast, saturated colors, placed well away from the P43 phosphor chromaticity, are the most salient. The number of distractors on-screen does not impact search time when a symbol is present. It is acknowledged that, in a practical CDNVG system, the additional dimension of luminance is available, and designers should be encouraged to adjust this parameter to reduce search times where possible. Finally, any choice of symbology color should be made in the context of existing cockpit displays and emitters, as well as aircrew experience and expectations, for example, if a particular flight parameter is always coded using amber or red, then aircrew safety, performance, (and morale) is unlikely to be improved by arbitrarily changing the coding of that color for a CDNVG display.

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