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Review of colored conformal symbology in head-worn displays

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ABSTRACT

The usage of conformal symbology in color head-worn displays (HWDs) opens up a range of new possibilities on modern flight decks. The capability of color augmentation seems especially useful for low flights in degraded visual environments. Helicopter flights in these conditions, including brownout by swirling dust or sand particles, can often lead to spatial disorientation (SD) and result in a significant amount of controlled flight into terrain (CFIT). While first generation color-capable conformal displays are deployed, practical guidelines for the use of color in these see-through interfaces are yet to be established. A literature survey is carried out to analyze available knowledge of color use in conformal displays and to identify established methodologies for human-factors experimentation in this domain. Firstly the key human factors involved in color HWDs are outlined, including hardware design aspects as well as perceptual and attentional aspects. Secondly research on color perception is mapped out, focusing on investigations of luminance contrast requirements, modeling of color space blending and development of color correction solutions. Thirdly application-based research of colored conformal symbology is reviewed, including several simulations and flight experiments. Analysis shows that established luminance contrast requirements need to be validated and that performance effects of colored HWD symbology need more objective measurements. Finally practical recommendations are made for further research. This literature study has thus established a theoretical framework for future experimental efforts in colored conformal symbology. The Institute of Flight Guidance of the German Aerospace Center (DLR) anticipates conducting experiments within this framework.

Keywords: color, luminance, contrast, helmet-mounted displays, conformal symbology

1. INTRODUCTION

The development of color in transparent conformal displays, i.e. color augmented reality, opens up a range of new possibilities on modern flight decks. The capability of color augmentation seems especially useful for low flights in degraded visual environment (DVE). Helicopter flights in these conditions, including brownout by swirling dust or sand particles, can often lead to spatial disorientation (SD) and result in a significant amount of controlled flight into terrain (CFIT).

Various studies have shown the necessity of effective visual aid technologies to increase situational awareness and reduce pilot workload in DVE conditions for safer helicopter flight. Research by the Dutch National Aerospace Laboratory (NLR) on European helicopter accidents from 2000 through 2008 found that over half of the cases was related to DVE or CFIT.[1] Similarly, an analysis of U.S. Army helicopter accidents between 2002 and 2011 identified 100 cases linked to SD and concluded SD to be linked to significantly more fatalities.[2]

Efforts to solve aforementioned problems have focused on either opaque, color head-down displays (HDDs) such as head-down enhanced synthetic vision display (ESVS), or on transparent, monochrome helmet-mounted displays (HMDs). An example of ESVS is the 3D Landing Zone (3D-LZ) concept by the U.S. Air Force Research Laboratory (AFRL) that combines sensory information to display a 3D obstacle map of a landing zone on a 2D color HDD.[3] Flight tests of 3D-LZ demonstrated safe landings and go-arounds though pilots were reporting high workload ratings.[4] Contrary to ESVS, HMD employs see-through visors along with head-tracking to provide the

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pilot with an unobstructed view of the environment over which symbology is conformally displayed. Extensive human factors studies of the use of HMD conformal symbology in DVE conditions confirm divided attention improvements and task performance but also stressed the risks of clutter in HMD symbology, potentially decreasing secondary task performance.[5]

The onset of color HMDs may contribute to mitigating problems in attention allocation and clutter. Color can encode information in symbology and allows a more intuitive presentation of information. However, guidelines for symbology design in color HMDs are yet to be established as only few human factors experiments have been carried out. This knowledge gap has to be filled to enable higher situational awareness and reduced pilot workload, ultimately leading to safer flight.

The objective of this literature study is to analyze available knowledge on color use in conformal displays and to identify established methodologies for human factors experimentation in this domain. By combining literature on color perception with application-based research on color conformal displays a theoretical framework will be established that should form a basis for future experimental efforts in human-centered HMD design.

Chapter 2 introduces human factor theories of color conformal display in Section 2.1, discusses optical modeling theory and color perception in Section 2.2, and analyzes studies on color HMD applications in Section 2.3. Chapter 3 consolidates the various approaches with a view to identifying present accomplishments and future challenges. In Chapter 4 a brief discussion leads up to an experimental methodology, followed by a conclusion to this literature review.

2. LITERATURE REVIEW

In the early 1990s, Melzer and Moffitt explained how various technological developments were encouraging the use of color HMDs.[6] Main arguments from a human factors perspective were visual performance gains in color coded HDDs, reduced workload, compatibility with population biases, alert accentuation and perceptual grouping. Moreover, the inception of head-tracked virtual reality displays eliminated the need for large dome simulators; more frequent nighttime missions in the air force demanded richer visualisation and size reductions in hardware enabled the installation in airframes. These initial observations were promising, but were lacking awareness about remaining problems. This literature review attempts to analyze overcome and remaining challenges since then.

HMDs may be considered as the technological successor of head-up displays (HUDs) as both employ transparent visors to overlay conformal symbology over the outside scene. HUDs project flight information at boresight direction only, whereas the head-tracking feature of HMDs allow them to show symbology at every viewing direction. The evolution of HUD is well-documented, providing a starting point for researching color see-through displays. Nevertheless, overlaying color over an outside scene in these displays leads to a rather unpredictable perception of the blended color by the pilot. This brings about specific characteristics that the designer must take into account.

Thorough understanding of the human factors involved in color HMD research is prerequisite, therefore an overview is given in Section 2.1. In previous work, the exploration of the technical and perceptual requirements of color HMD is predominantly approached from two angles: color perception and application testing. Relevant studies with respect to color perception attempt to experimentally determine the blending of outside scene and symbology colors. They are reviewed in Section 2.2. The application-based approach essentially follows a trial-and-error strategy by designing color HMD symbology and by performing human factors experiments. Each subsequent iteration uses lessons learnt from the previous cycle until an acceptable solution is found. Those studies in question are reviewed in Section 2.3.

2.1 Human Factors of Color HMD

This work focuses on those elements of human-machine interface design that are relevant for colored conformal display. Other aspects relating to conformal display in general are outside of the scope of this study. Nonetheless Section 2.1.1 will first mention some technical characteristics of HMDs that come into play with perceptual and attentional issues of color HMDs, ensuingly discussed in 2.1.2.

2.1.1 Design Aspects

The vertical and horizontal angles at which a head-worn device can draw information visible to the eye define its field of view (FOV). A high FOV is desirable to decrease the necessity of turning the head and improves user performance at various tasks.[7,8] Binocular displays present each of the user's eyes with a different image. This enables a large field of view (FOV) with stereoscopic depth cues.[9] The level of detail that can be shown in a display is defined as the resolution, i.e. the image fidelity. It is often specified in an amount of horizontal and vertical pixels. Resolution dictates the smallest element that can be shown, but the minimum human visual resolution of 1 minute of arc is out of reach for current generation color see-through displays.[9]

The legibility of symbology on a semi-transparent screen is primarily governed by its luminance and contrast capacities. High luminance is required for an image to be visible against bright backgrounds. Contrast ratio specifies the maximum luminance ratio between adjacent areas. High contrast ratio images are clearly visible whereas low contrast produces washed-out images.[10] Another defining feature of HMDs is head-tracking. By measuring changes in head position and orientation the image is updated to remain fixed with the outside scene. This creates the illusion of a natural viewing condition. Accurate and low-latency head-tracking is required to prevent disorientation, nausea and motion sickness. The critical lag threshold is somewhere between 16 and 80 ms.[11] Thanks to collimation, symbology is displayed at optical infinity, eliminating the need to re-accommodate when switching from far domain to symbology.[12]

2.1.2 Perceptual and Attentional Aspects

Perceptual and attentional issues in HMDs are well-documented.[11,13] Most findings are based on the Integrated Helmet and Display Sighting System (IHADSS) which was the first integrated monocular HMD for the AH-64 Apache helicopter. It was introduced in the 1980s and featured a head-tracked Forward Looking Infrared (FLIR) image for night operations.[7] Issues associated with IHADSS usage include higher workload and stress as well as visual and mental fatigue.[10] However the applicability of these findings to our work is uncertain since binocular HMDs are likely to solve most problems. These are becoming widely available.

Recently, Knabl has reviewed perceptual and attentional aspects in HMDs. Visual aspects covered include visual acuity, accommodation, vergence and binocular rivalry.[5] Attentional problems discussed are attention allocation, visual search, attentional tunnelling and unexpected event detection.[14,15] These issues form an important part of any research on conformal symbology display, although our discussion will further focus on the specific impact of color on HMDs.

Fares and Jordan surveyed important variables in colored conformal displays and found that perceptual issues complicate any suitable research method.[16] The first problem identified is a lack of definition. Color has no clear definition, but is rather viewed as a perception. Moreover the neural interpretation of visual stimuli is only a part of the decision-making and situational awareness processes. Recognition of colors is affected by individual traits such as memories or other associations. Color is the response from the visual-neural system to material properties (e.g., reflectance of an object, etc.), and its perception is more complex than the sum of isolated processes. This justifies that user response should be weighted equally against hardware capabilities.

The second issue described is that the impact on situational awareness and decision-making of the physiological processes involved in viewing color on a transparent visor over a colored textured outside scene is unknown. An attempt is made to identify the role of color at the mission level. Mission performance is considered to be affected by situational awareness and decision-making. System components are the eyes-out device and the content it displays. The design drivers are then coding of the information, the level of transparency of the display and the pilot's perception. Describing these components in terms of observables was then unsuccessful as the perception component was not deducible from the situational awareness and decision-making variables.

Fares and Jordan recommend that display tests on colored symbology be conducted, to be complemented by actual human performance experiments with challenging assignments to put design iterations to the test. Good practices are prescribed as well. Their recommendations actually describe the two main approaches that have been employed in past research. Color perception research will be discussed first in the next section, followed by application-based research.

2.2 Color Perception Research

A baseline requirement for using color in HMDs is that it can be recognized. This is mostly determined by luminance contrast: the ratio of luminance between two adjacent elements, usually a symbol and its background.[17] Higher luminance contrast means the color of a symbol can more easily be distinguished against its background.

Researchers involved in the U.S. Air Force Research Laboratory's (AFRL) Helmet Mounted Sight Plus (HMS+) program in the late 1990s conducted a series of experiments on luminance contrast and color recognition in see-through displays. The first experiment determined the requirements for minimum visual recognition of color.[18] Ten participants viewed a selection of representative outside scenes on a monitor. The scenes were superimposed by green, yellow and red symbology which was added to the background color to simulate a see-through display. Luminance contrast was increased until participants could recognize the color. Colors were said to be recognized at an average contrast ratio between 1.12 and 1.18, which is quite low. Yet for some combinations subjects wrongly identified the color, while red symbology was consistently identified. The authors concluded they had found minimum contrast while looking for sufficient luminance contrast.

A follow-up experiment found that users overestimate their perceptional abilities and that red is consistently recognized.[19] A similar experimental setup was used to find the sufficient luminance at which at least 95% of background-HUD combinations was correctly identified and alphanumerics could be read. With the exception of one color combination (hazy sky with yellow target) the luminance contrast ratios were found to be between 1.07 and 1.15 when a single color was used for the whole symbol set. For character legibility a similar range was found. Two observational lessons were drawn from these studies. Firstly users are susceptible to overestimating their ability to identify symbology color, underlining the necessity of a minimum luminance contrast threshold. Secondly the color red is not easily misidentified, reassuring designers and users when dealing with critical information.

In 2005 and 2007 a series of experiments at the U.S. Army Aeromedical Research Laboratory (USAARL) found a minimum luminance requirement of 2.28 times the ambient background luminance.[20] An HMD simulation model was developed in parallel with the experiments. In the first study, subjects judged the quality of symbology overlaid on various backgrounds of varying complexity, of which the average contrast value was varied. Unsurprisingly background complexity was found to affect observer ratings. The metric model that was developed relates symbology luminance to the standard deviation of small patches of background around the symbols. The model was then used to find a minimum luminance requirement of 2.28 times the ambient background luminance measured at the eye. In the second study small patch luminance and complexity of the static background images were analyzed to improve the previously found luminance requirement.[21] The luminance-complexity curve developed is usable as a framework for determining the minimum luminance requirements for any range of outside scene luminance for other HMDs.

The work by the AFRL and USAARL employed empirical approaches towards finding color HMD luminance requirements. The luminance requirements offer a starting point for further research and additional human factors experiments should at least include the numbers cited as a reference and for validation. The problem with the approach employed is that it does not increase the understanding of the mechanism of color blending. How to assure that colors projected on a see-through display are effectively perceived even after blending with the outside scene?

This question lead Gabbart et al. to conduct an empiric study to determine the blending of real and virtual color spaces.[22] An optical augmented reality testbed was created using a transparent color display and a number of selected background colors. The display drew 27 colors while scene lighting was also varied. Resulting blended colors were measured by a colorimeter. Even though a formalized color blending function was formulated, the authors did not succeed in quantitatively relating their measurements to the model. Instead, four qualitative categories were found in a brief follow-up publication: washout due to chromaticity, luminance or both and linear chromaticity shift.[23] These observations help understand color blending in augmented reality but the practical implications remain unclear. The selection of colors used lacks a theoretical justification. Perhaps more useful results could be found with the same experimental testbed if the inputs are designed for a specific model identification method.

The lack of a quantitative relation of color blending did not stop the development of color correction solutions. Various proofs of concept were made. One uses a simplified model for tone reproduction of an image under eye adaptation.[24] Another adopted binned profiles to predict color blending and measure the correctability.[25] This approach showed that light display colors can more effectively be corrected for all backgrounds. An important recommendation for further research is to collect the prevalent background colors of the intended application in order to select a color palette that is best corrected by a potential reproduction algorithm.

The same authors advanced the state-of-the-art by implementing a correction for the distortion due to the transparent visor and by further improving the color correction algorithm.[26] A user-based test showed participants judged adjusted colors more often to be closer to the desired colors than the originals. The algorithm was implemented as a 2D vertex shader using the OpenGL graphics library and recommendations were made to extend it for 3D and texture support.

2.3 Application-Based Research

The Aeroflightdynamics Directorate (AFDD) of the NASA Ames Research center has not prescribed strict criteria for color HMD but has instead offered general recommendations.[7] The AFDD provides engineering knowledge for and from military aviation systems development. In 1997 the AFDD published an HMD design guide that, on the subject of color, blamed a lack of experience for the absence of a design methodology. However the following design rationale was provided that should guarantee effectiveness and robustness when designing for a color HMD.

- Colors should only be used where an improvement over monochrome symbols can be shown.
- Colors used should be consistent with head-down instruments.
- Each color should provide acceptable contrast against all likely background conditions.
- Color should be used redundantly.
- Color displays should have a monochromatic mode that is legible in all conditions.

Two studies by Geiselman et al. tested an application that demonstrated the AFDD's first guideline. The earliest study tested various color coding strategies during air-to-air combat task simulations.[27] Color symbology was displayed directly on the outside scene in a dome simulator. All six fighter pilots with combat experience preferred colored over monochrome symbology. Interestingly all pilots preferred a red means shoot color coding strategy over green means go. The second study assessed whether the preferred color-coding strategy gave rise to a performance advantage compared to monochrome symbology.[28] A realistic multiplayer air-to-air combat scenario involved a range of demanding tasks in a simulator. The twelve fighter pilots from the U.S., U.K. and Sweden praised the color symbology and objective performance measures indicated a substantial advantage for color coding.

Although the Geiselman et al. studies were effective at demonstrating the benefits of color coding, luminance and chromaticity were confounded.[29] The challenging design of the combat task pushed the pilots to high workloads and so performance effects could be identified. However these studies attribute performance enhancements solely to color, i.e. chromaticity. It is not verified whether different colors were displayed at equal luminance. If practically possible, this confound should be prevented in future experiments.

In 2006 and 2007 Boeing performed flight testing on a small MD-530 helicopter to demonstrate an ESVS with colored conformal symbology in DVE.[30] Sensory information from a variety of fixed and turreted sensors and symbology were simultaneously available to the pilot on a monochrome, semi-transparent HMD and to a remote user through full-color, virtual reality glasses. Sensor imagery was stitched in real-time and integrated with color textured synthetic imagery and color symbology, including a purple highway-in-the-sky, gridded domes for obstacles and a green pitch ladder. Pilots found that color added meaning and aided interpretation of information. Synthetic vision degraded the image quality on the semi-transparent HMD, these problems may have been the result of occlusion, unsatisfied luminance requirements and clutter.

Flight testing by NASA showed that traffic diamonds shown in color on a HMD greatly reduced clutter.[31] Approach and taxi testing were done on a King Air aircraft in varying visual conditions. Participants reported they could intuitively disregard or focus on colored symbols when needed, decreasing clutter and increasing visual search time. Pilots liked the increased situation awareness of the HMD compared to a HUD and task performance was qualitatively judged to be equivalent. Recommendations were made for directly comparing HUDs to HMDs in future experiments.

The Defense Advanced Research Projects Agency (DARPA) demonstrated color coding in a wearable tactical support system called ULTRA-Vis.[32] The monocular system displays conformal icons over the environment. Military standards were used for color coding: icon shapes for hostile, friendly, neutral, and unknown were marked red, cyan, green, and yellow, respectively. System graphics were green and symbol sizes were not scaled with relative distance to increase visibility. Distances to objects were shown because of the monocular setup. Display symbology was designed after a cognitive task analysis was done to support the warfighters' decision-making process. The authors noted that outside scene and display luminance must be balanced for legibility and comfortable viewing.

3. RESULTS

This paper has identified how two different experimental approaches are used to discover if and how color conformal displays are could effectively be used in aeronautical applications. On the one hand focus is put on the perceptual aspects of color, while on the other hand a more practical approach is pursued involving trial and error. From these two research strategies, several important findings were made and a multitude of challenges were encountered.

Minimum luminance contrast needs to be assured for all mission scenarios and visual flight conditions where color conformal display is implemented. Controversy exists in experimentally obtained minimum luminance contrasts, since colored symbology resulted in a contrast ranging of 1.07-1.15 and white symbology led to a ratio of 2.28. Both methods used static backgrounds, while minimum contrast for a dynamic background would be lower.

Aside from luminance requirements, color correction algorithms can contribute by counteracting color blending to help achieve functional color perception. Light display colors can be corrected most effectively. A limitation is that the symbology color palette should be selected for prevalent background conditions to increase correction effectiveness, while color coding should remain consistent with HDDs.

A design philosophy is available which aims to exploit the advantages of color coding while mitigating potential pitfalls with consistent and robust design. Practice-oriented experiments with color coded symbology have followed these guidelines. Various implementations confirmed that color conformal symbology has the potential to increase task performance and situational awareness, while decreasing clutter, workload and visual search time.

4. DISCUSSION AND CONCLUSION

Analysis of the reported literature has shown that formalisation and specifically quantification of color blending in semi-transparent displays remains a challenge. Effectiveness and efficiency of already developed correction algorithms may be augmented with the availability of a color blending model. Further investigation of luminance contrast requirements is needed as well, preferably integrated within an application-oriented testbed to evaluate laboratory findings if a test setup is used that can replicate natural background luminance.

Most conclusions of application-based studies were established primarily on subjective pilot ratings. While these are certainly helpful in a design cycle, future studies should emphasise more on objective measurements of task performance to remove user bias. Moreover, each additional element in a coloring strategy should be assessed against a baseline monochrome version to ensure each design choice is justified.

Thus, a knowledge gap remains between color perception theory and human machine interface design in colored conformal displays. This gap can only be bridged by simultaneously addressing both aspects in order to determine colored conformal display guidelines. Color use was not the main focus in the few flight tests that have been reported to use color see-through displays. Moreover, the described experiments using flight simulators exploited software emulations instead of augmented reality displays. Therefore, it is strongly recommended to test various color coding strategies in HMDs by using reproducible simulator experiments.

Section 2.1 has underlined the most important human factors involved in our discussion. Though outside the scope of this study, these factors are best described within object-based theories of attention as described by Knabl.[5] Any implementation of conformal display in HMDs should at least use this theoretical framework, regardless of the theoretical basis for using color.

Based on the foregoing literature analysis, the following recommendations are made for human factors experiments with color conformal displays:

- Minimize the amount of symbols used;
- Apply shape/color coding redundancy;
- Color code shared meanings;
- Limit the amount of colors used;
- Adjust luminance independently from chromaticity;
- Respect existing color coding conventions;
- Design demanding flight tasks for high workloads;
- Measure situational awareness and workload aside from objective performance.

This paper has demonstrated that the establishment of effective colored conformal display design guidelines first requires integrating the color perception component into application-based experimental setups, such that a consistent and comprehensive body of evidence is obtained. While part-task experiments may first help determine general design guidelines for color HMD, complex mission scenarios could subsequently aid in finding more advanced color coding strategies to augment situational awareness or decision-making.

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