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Benefits of Color Coding Weapons Symbology for an Airborne Helmet-Mounted Display

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We assessed the advantages of a color-coded weapons symbology for a helmet-mounted display over monochrome symbology by measuring military pilots' performance while they flew air-to-air combat in a simulator. The pilots fired missiles significantly sooner without sacrificing probability of kill when using the color-coded symbology, demonstrating a substantial practical benefit of color. Actual or potential applications of this work include the design of color codes for helmet-mounted and other displays that use complex symbology to assist performance on cognitively challenging tasks.

INTRODUCTION

The U.S. Air Force Research Laboratory's Helmet-Mounted Sight Plus (HMS+) program is developing a color helmet-mounted display (HMD) to enhance information conveyance to the pilot. HMS+ is essentially a color-capable version of the Visually Coupled Acquisition and Targeting System (VCATS) HMD, which has been developed mainly to support missile aiming over a large range of pilot head positions and orientations. This aiming ability is a major advantage of HMDs over head-up displays (HUDs), as Barnes (1989) pointed out: "The target is outside the HUD field-of-view during most tactical maneuvers and offsets. The farther off the target can be detected and tracked, the more effective the intercept tactics can be" (p. 149). The potential benefits of HMD-presented information have been demonstrated in the laboratory and in flight tests (Geiselman & Osgood, 1994, 1995; Osgood, Geiselman, & Calhoun, 1991).

A full-color capability may be desired ultimately for more versatile HMDs, but the HMS+ program is developing a two-primary, red + green (RG) HMD using a subtractive-color active-matrix liquid-crystal display (AMLCD) as the image source (Post et al., 1994; Post, Dodd, Heinze, & Shaffner, 1997). Subtractive-color AMLCD technology has been selected because it provides better image quality than do conventional additive-color AMLCDs in this application (Post & Reinhart, 1997). An RG display can produce reds, greens, and all the intervening hues (i.e., oranges and yellows) but not whites, grays, blues, purples, or cyans. The RG color repertoire should be adequate, though, given the limited intended application for HMS+. Furthermore, for a subtractive-color AMLCD, the use of RG instead of full color reduces the manufacturing cost by 39% and increases the display's transmittance two to four times (Franklin & Reinhart, 1997).

In a previous study (Geiselman et al., 1998), we developed two color-coded versions of the VCATS weapons symbology using the RG color repertoire. Six U.S. Air Force fighter pilots with HUD and air-to-air weapon delivery experience evaluated the color codes after testing them while flying an air-to-air scenario in a simulator. All six pilots preferred the color-coded symbology to the monochrome VCATS baseline. Furthermore, and perhaps surprisingly, a "red means shoot" color-coding strategy (which involved a progression from green to red as an indication of shoot-criteria satisfaction) was preferred unanimously to a

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"green means go" strategy (which involved a red-to-green progression).

Although the general merits of color coding – particularly for speeding visual search – are well documented (Post, 1992; Silverstein, 1987; Travis, 1991), it is not obvious that color coding HMD air-to-air weapons symbology should have measurable and important performance benefits, pilot preference notwithstanding. The purpose of the present experiment was to determine whether any such benefits can be demonstrated for the "red means shoot" code.

METHOD

Participants

Twelve volunteer military pilots from the United States, the United Kingdom, and Sweden participated. Their mean flight time was 2448 h. Ten pilots had experience in HUD-equipped fighters, four had in-flight HMD experience, and nine had air-to-air missile launch experience.

Apparatus

We used a projection dome having a 20-foot (6 m) radius with an F-16 cockpit mockup that included a single throttle, a force-type side stick controller, a HUD, a radar scope, an attitude indicator, and a horizontal situation indicator. The simulation software used an F-16 aerodynamic model. The dome provided a 150° horizontal by 70° vertical visual scene, which was produced by six color CRT projectors. The HMD was simulated by drawing the symbology on the dome, superimposed additively on the outside scene by the graphics processor, within a 20° circular field of view (FOV) that was centered at the participant's line of sight (LOS). The LOS was measured by a magnetic head tracker. To simulate the action of a real cockpit HMD, the HMD was blanked when the tracker indicated that the participant was looking down at the panel instruments or HUD. A black-sky outside-world scene was used to reduce secondary reflections from the curved projection screen and thereby to increase color saturation and luminance contrast.

HMD Symbology

The luminances of the red, green, and yellow symbols were 0.20, 0.65, and 0.85 cd/m^2, respectively, when measured against the black sky. These luminances are typical of large dome simulators, and although they may seem low, the symbol colors were easily recognizable against all the backgrounds. The ratios among the luminances are roughly what would be expected for a real airborne color HMD, given that airborne HMD luminance must often be maximized to improve visibility and that color displays typically provide a much higher peak green luminance than peak red. Symbol contrast ratios ranged up to 3.7:1, depending on the combination of symbol color and background, and were therefore representative of the contrasts one might expect to achieve for daytime viewing of a real airborne color HMD.

We used the VCATS symbology (see Figure 1), which is similar to existing HUD symbology and therefore familiar for most tactical pilots. It was green in our monochrome conditions. It includes several functionality groups, but only those relating to target location, tracking, and weapons deployment were color coded, so we will discuss only those groups. Geiselman et al. (1998) described the symbology more completely.

Target designator box group. The target designator (TD) box symbols showed an extrapolated primary designated target (PDT) LOS when the target was within the HMD FOV; that is, within a 10° radius of the HMD center point. This symbology, like all other targeting-specific symbology, was present only when a radar PDT was established. The box symbols were superimposed on the target location in the outside scene. The TD box was replaced by a target locator line whenever the target was within the sensor field of regard but beyond the HMD FOV. Only one PDT could exist at a time. Information around the box included a shape-coded identification friend or foe (IFF) symbol on the left side.

Above the box, an alphanumeric readout showed either target recognition information (e.g., aircraft model identification) or the number of degrees (if fewer than 10) before the target would reach the onboard radar's maximum coverage angle. (This number is known commonly as *degrees before break-lock.*) Alphanumeric indications of target range and altitude were attached to the right side of the

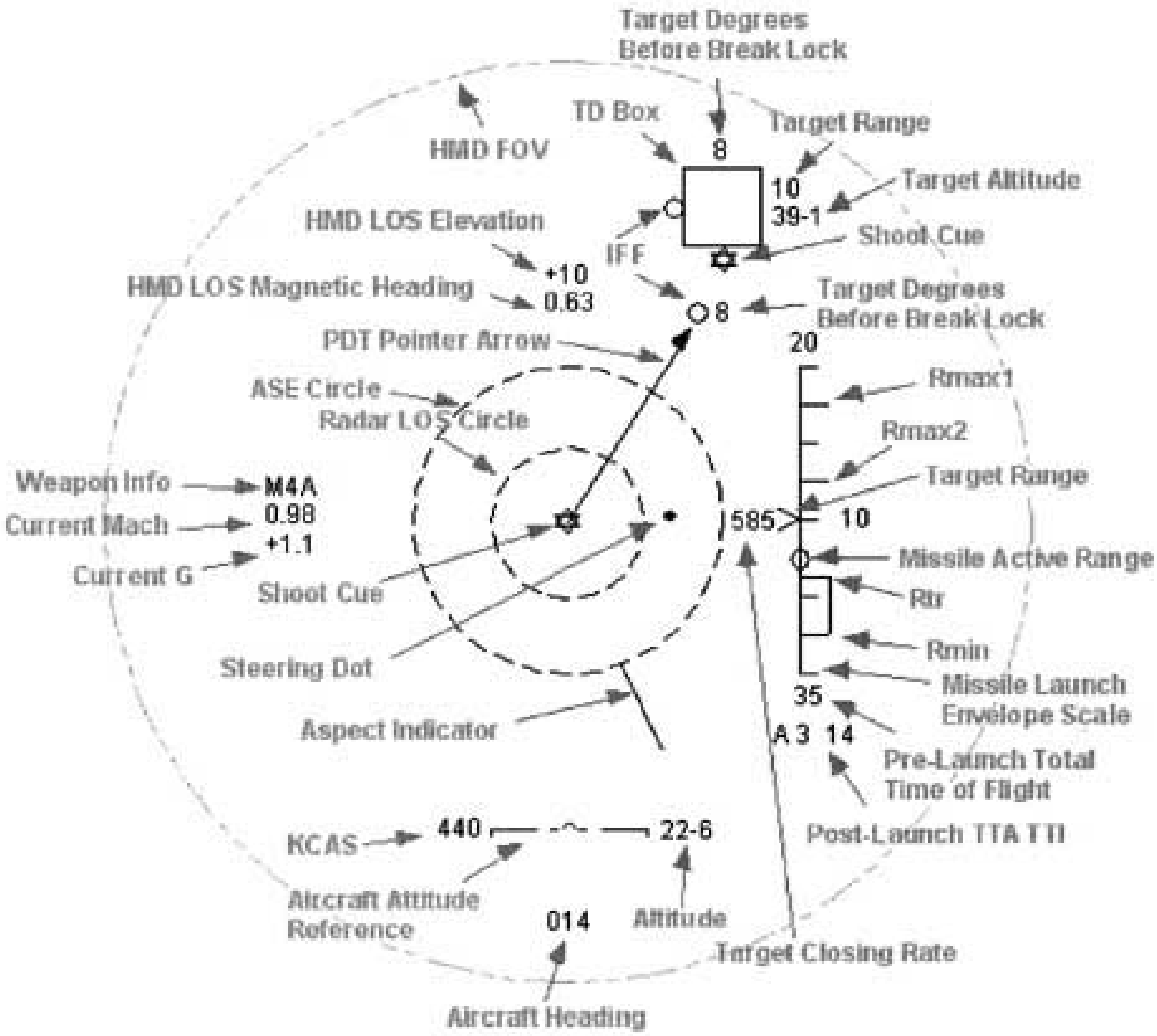

Figure 1. VCATS symbol set.

box. The bottom side was reserved for the appearance of a star-type shoot-cue symbol when the launch parameters for the current selected weapon were satisfied.

The color coding for the TD box group varied between green and red depending on the missile launch solution. The TD box was green if the PDT was outside the missile's maximum or minimum allowable launch ranges. Within the maximum flight ($Rmax_1$) and maximum terminal phase maneuvering ($Rmax_2$) PDT ranges, the TD box changed continuously from green to yellow. Within $Rmax_2$, the TD box snapped to red. These color changes indicated the transition of the PDT from out of range to within minimal launch parameters and, finally, to within a high probability of success launch range.

The TD box remained red within the $Rmax_2$ and minimum launch (Rmin) ranges. Inside the Rmin range, the TD box snapped back to green to indicate the return to an out-of-limits state. Additionally, the inside-Rmin state was indicated by the presentation of a green break *X* symbol (not shown in Figure 1), drawn across the center of the HMD FOV. Presentation of the shoot cue symbol associated with the TD box (and locator line; see next paragraph) indicated a within-good-launch-parameters state; therefore, the shoot cue symbol was always red. The degrees-before-break-lock alphanumeric associated with the TD box and locator line was always yellow because this information, when it appeared, indicated an approaching-limits condition. Symbols representing friendly IFFs were green, unknown targets were yellow, and hostile targets were red; this system conforms with conventional IFF color coding.

Target locator line group. A target locator line showed the continuously computed combined azimuth and elevation vector to the PDT LOS when the PDT was located outside the HMD FOV. The locator line and TD box did not coexist. Accordingly, the line also had IFF, degrees before break-lock, and shoot cue symbology attached to it. The line was anchored at the center of the HMD FOV and radiated out toward the edge of the HMD FOV. The outside end of the locator line was a solid arrowhead. The length of the line changed dynamically in proportion to the angular difference between the HMD LOS and the PDT location, up to 45°. Beyond 45°, the line was drawn at its maximum length of 7.8°. Between 45° and the point where the target crossed within the HMD FOV, the locator line shortened to its minimum length of approximately 2°.

A shape-coded IFF symbol was attached to the locator line arrowhead. A circle indicated a friendly return, an *X* indicated an unidentified return, and a diamond indicated a hostile target. A degrees-before-break-lock readout was displayed next to the IFF symbol if the PDT was within 10° of the maximum radar coverage. A shoot cue was displayed at the locator line anchor when the launch parameters for the selected weapon were satisfied for the PDT. The locator line's color coding matched that for the TD box.

Allowable steering error circle group. The allowable steering error (ASE) circle was a boresight-referenced repeater of the same symbology presented on the HUD. A comparison of the dynamic steering dot with the edge of the ASE circle indicated the instantaneous quality of the missile launch relative to the weapon's lateral and vertical limitations. The radial aspect indicator line represented the PDT's aspect angle relative to the ownship flight path.

The ASE circle was green, but the associated steering dot was color coded according to its proximity to the ASE circle. Within the circle, the steering dot was red to indicate within allowable steering error. Outside the circle, but within 2° of it, the dot was yellow. Beyond 2° the dot was green. The radial target aspect line attached to the ASE circle was color coded depending on the nose-versus-tail aspect relationship between the ownship and target velocity vectors. The line was red from 270° to 90° (across the top) aspect angle to indicate that the ownship nose was oriented to the target's tail. A yellow line between 90°–110° or between 270°–250° indicated an approaching neutral aspect. A green line between 110° and 250° indicated neutral.

Dynamic launch range group. This symbology showed the PDT range and closure rate along the left side of a fixed scale. The scale's right side showed significant launch parameter ranges for the selected weapon. When the PDT was within the $Rmax_2$–Rmin envelope, a shoot cue associated with TD box or locator line was presented. If the PDT was between the target turn-and-run range (Rtr) and Rmin, the shoot cue symbol flashed at 5 Hz. A break *X* symbol (not shown in Figure 1) was drawn across the center of the HMD FOV if the PDT range was inside Rmin.

The range bars on the dynamic launch range scale were colored to indicate the launch limitations they represented. The $Rmax_1$ bar was yellow and the $Rmax_2$, Rtr, and Rmin bars were red. The line that connected the Rtr and Rmin bars to indicate the Rtr region was also red. The dynamic target range and closure rate caret were colored to show the launch envelope region in which the target was located. The caret was green beyond $Rmax_1$ and within Rmin. Within the $Rmax_1$–$Rmax_2$ region, the caret changed from green to yellow. The caret snapped to red as the target crossed into the $Rmax_2$–Rmin region.

Scenario

The scenario was a multiplayer air-to-air engagement involving hostile bombers, friendly fighters, unknown fighters, and hostile fighters. The gaming area was a 60 × 50 nautical mile (nm) portion of the Defense Mapping Agency southwest U.S. database, and the Truth or Consequences Airport near Albuquerque, New Mexico, was home plate. The scenario involved the combined use of head-down radar functions and HMD-provided target location information to perform target acquisition, radar lock, identification, and missile launch. There were four mission phases: combat air patrol, intercept, attack (bombers and fighters), and egress. Our interest focused on the intercept and attack phases.

The six players were the primary cockpit (ownship, flown by the participant), two manned fighters, an autonomous friendly fighter, and two autonomous enemy bombers. The manned fighters were flown by experienced laboratory personnel via auxiliary stations and changed identification (i.e., from unknown to either friendly or hostile) according to the experimental design. Their tactics were coordinated by an air-to-air tactics expert acting as an Airborne Warning and Control System (AWACS) controller (red controller). The primary cockpit was given AWACS-type information by the experimenter (blue controller). The controllers viewed wall-projected bird's-eye views of the gaming area and on-demand status information about each aircraft. The players communicated via an intercom that allowed the experimental participant to hear only the blue controller and everyone else to hear all other communication.

For each trial, the bombers started from one of four possible, randomly chosen locations and then tracked directly toward home plate, flying 1 mile apart in a trail formation. Five waypoints, connected to form a closed course, were used as fighter start locations. The autonomous friendly fighter, which served as a distracter for the participant, started from a waypoint adjacent (either left or right, chosen randomly) to the bomber start location and then also tracked directly toward home plate. The manned fighters started from the waypoint adjacent to the bomber start location and opposite the friendly distracter location. As long as the manned fighters were designated "unknown," they followed the closed course counterclockwise in formation from waypoint to waypoint at 15 000 feet and 480 knots. If their identification switched to friendly or hostile, they maneuvered according to the red controller's directions. Hostile fighters maneuvered aggressively against the ownship but did not fire on it. (The ownship was instructed to fly nonetheless as if hostiles could fire.) Friendly fighters maneuvered to cause confusion.

Rules of Engagement

Starting from home plate at 15 000 feet and 480 knots, the ownship pilot was directed by the blue controller toward the two approaching bombers via radar vectors, with instructions to identify and shoot them down. While the ownship maneuvered, the blue controller gave snap-look location information about other "unidentified" targets in the area. These targets appeared on the ownship radar when they were within the coverage volume. The ownship could select one PDT at a time using either the conventional radar display (which had a 40-mile range and ±60° field of regard) or the HMD.

The ownship pilot was instructed to monitor the other aircrafts' movements during the bomber attack. Once the bombers were defeated, the ownship concentrated on the secondary targets. During the bomber attack mission phase, the manned fighters followed the prescribed waypoint route, and the ownship IFF, which was available only on the HMD, showed them as unknowns. Once they reached their first waypoint (this took 3–5 min), their IFF indications could change. The ownship rules of engagement depended on the indications. Friendly targets could be ignored, and if only friendlies remained, the ownship was to egress toward home plate. If the IFF was unknown and the target was approaching home plate, the ownship was to intercept and track it. If the unknown turned away from home plate, the ownship was to egress. If the IFF was hostile, the ownship was to shoot the target down. The ownship was also to egress if all hostiles were shot down or all eight missiles were used. The trial ended when egress commenced.

Procedure

For training, each participant read instructions, examined color figures of the symbology set, listened to an oral description of the task, free-flew for 30 min to become familiar with the simulation, and then experienced several full-scenario practice trials. Questions were addressed as they arose during both training and experimental trials.

Each participant completed all four 1-h experimental sessions in one day, with rest pauses given as needed and a lunch break at the halfway point. Each session consisted of 8 trials, yielding a total of 32 trials per participant. The use of color-coded HMD symbology alternated across sessions: Even-numbered participants began with color-coded symbology and odd-numbered participants began with monochrome. Thus HMD color was a within-subjects variable. The start locations of the bombers, manned aircraft, and distracter friendly, and also the manned aircraft identifications (i.e., both switch from unknown to friendly, both switch to hostile, one switches to friendly and the other switches to hostile, or both remain unknown), were balanced across trials for control purposes but were not factors in the subsequent analyses. All simulation data parameters were recorded at 5 Hz, and all trials were videotaped.

RESULTS

For each launch we computed the target's PDT time prior to the shot and the target's range at the time of the shot. These PDT times showed positive skew, so we log-transformed them. We sorted launches into three probability-of-kill (Pk) categories according to the shoot cue indications that were present at launch time: A flashing shoot cue denotes the highest Pk, a nonflashing cue denotes medium Pk, and an absent cue denotes low Pk. We also differentiated between launches against bombers and launches against hostile fighters because these target types call for different attack and maneuvering tactics. We calculated a mean $\log_{10}$ PDT time and mean target range for each Participant × Pk × Target Type × HMD Color combination, dropping cells having fewer than two observations. One-way analyses of variance (ANOVAs), using HMD color as the main effect, were then performed for each combination of Pk and target type, using only participants who had no missing cells.

Flashing Shoot Cue

PDT time for this case was computed as the difference between the time at which the cue started flashing and the time at which the launch occurred. For bomber launches, 7 participants had no missing cells; for hostile fighter launches, 11 had no missing cells. The mean $\log_{10}$ PDT times and mean target ranges for these participants are shown in Figure 2. The ANOVAs showed that HMD color had no significant effect on PDT time for bombers, $F(1, 6) = 0.03$, $p = .8578$, but color coding reduced PDT time significantly for hostile fighters, $F(1, 10) = 11.08$, $p = .0076$. The difference between the reverse-transformed (i.e., geometric) means for the fighters is 1.24 s. HMD color had no significant effect on target range at launch time for bombers, $F(1, 6) = 0.01$, $p = .9431$, or hostile fighters, $F(1, 10) = 0.05$, $p = .8262$.

Nonflashing Shoot Cue

PDT time for this case was computed as the difference between the time the cue came on and the time the launch occurred. For bomber launches, 10 participants had no missing cells; for hostile fighter launches, there were only 7 shots in the monochrome condition and 14 in

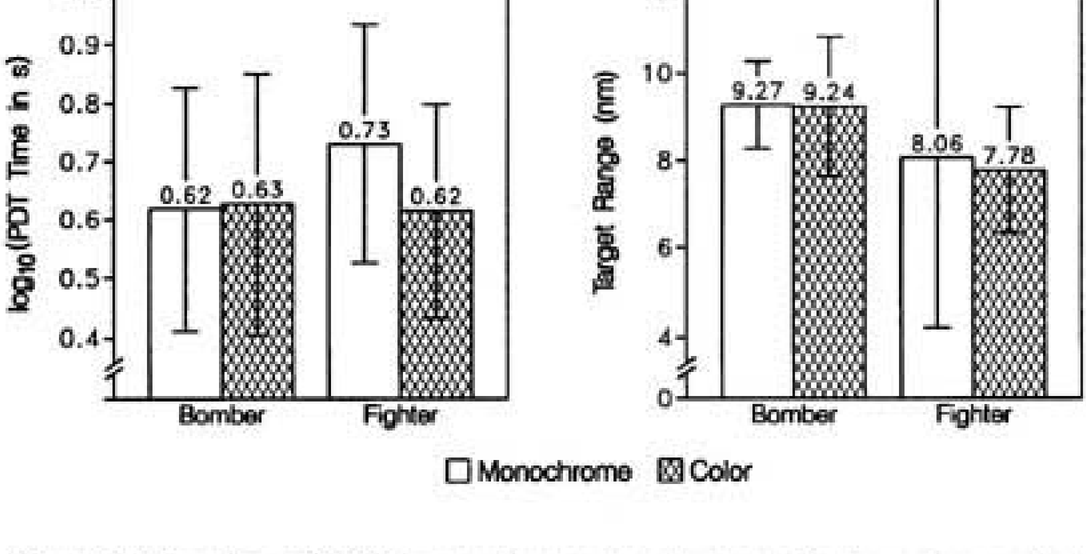

Figure 2. Mean $\log_{10}$ PDT times and mean target ranges for launches against bombers and hostile fighters when the shoot cue was flashing. Whiskers show standard deviations.

the color-coded condition, so we did not perform ANOVAs for fighter launches. The mean $\log_{10}$ PDT times and mean target ranges for bombers are shown in Figure 3.

The ANOVAs showed that color coding reduced PDT time significantly, $F(1, 9) = 5.85$, $p = .0387$, and increased the target range at launch time significantly, $F(1, 9) = 6.02$, $p = .0366$. The differences between the PDT-time geometric means and target range means are 1.58 s and 1.17 nm, respectively. A 1.17-nm difference has no practical effect on Pk for a nonmaneuvering target, so although there is presumably a causal relationship between the reduced PDT times and increased target ranges, we conclude that the participants shot sooner without sacrificing shot quality in the color-coded condition. The sparse data for fighter launches show the same trend.

Shoot Cue Off

There were not enough launches for this case to permit reasonable ANOVAs; however, the data resemble those for the nonflashing shoot cue.

Target Identification

We expected that friendly and unknown targets would be fired on occasionally and that these errors might be less frequent when the IFF symbology was color coded. There were four launches against friendly targets and seven against unknowns, but the videotapes showed that none was attributable to HMD color.

DISCUSSION

Our results show that the "red means shoot" color code, when applied to the VCATS weapons symbology, produced significantly faster shots against fighters and bombers without degrading Pk. For fighter targets this advantage was demonstrable only for flashing shoot cues, whereas for bomber targets it was demonstrable only for nonflashing shoot cues. This difference almost certainly reflects a difference in tactics: Military pilots know that launches against agile fighters should be delayed until the best possible launch solution is available, whereas launches against bombers can be successful under less optimal conditions. Furthermore, in our scenario, it was important to shoot the bombers quickly and move on to the fighters.

Our best estimates of the average time reductions attributable to color coding are 1.24 and 1.58 s against fighters and bombers, respectively, albeit for different launch solutions. These might not seem to be substantial differences, but in contemporary air-to-air combat, even fractions of a second can have life-or-death consequences. Viewed from this perspective, the time savings demonstrated here are impressive,

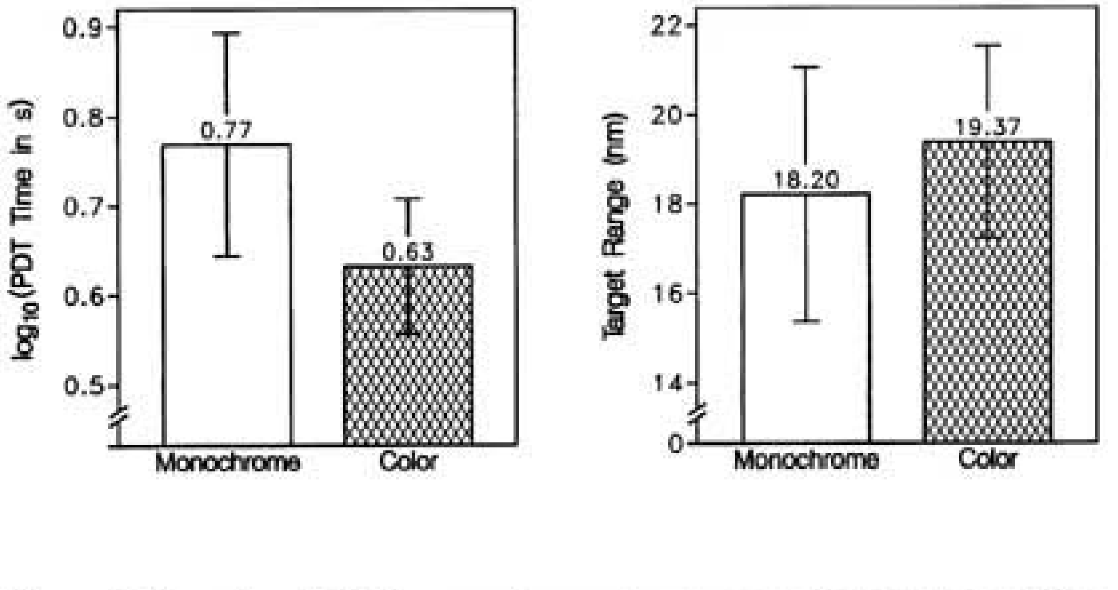

Figure 3. Mean $\log_{10}$ PDT times and mean target ranges for launches against bombers when the shoot cue was on but not flashing. Whiskers show standard deviations.

and even if they were only half as great in the more complex environment of real combat, they would still be sufficient to make color HMDs worth serious consideration.

The lesson of more general interest here is that careful design can yield a color code that gives important performance benefits, even in complex tasks that have no significant visual search component and in which other factors might be expected to overpower a color effect. Demonstrations such as this are scarce in the literature.

One might wonder whether our color code's advantage is related to luminance contrast rather than color. Our contrast ratios were often below the 3:1 minimum that the American National Standards Institute (ANSI, 1988) and ISO (1992) recommend for visual display terminals, and perhaps it was simply harder to read the green symbols. However, the color-coded condition was actually the disadvantaged one in this respect, because although luminance contrast was slightly higher for the yellow symbols than for the green ones, it was much lower for red. Further, our figures show that most launches occurred at least several seconds after the shoot cue appeared, which is too long a delay if the pilots were merely shooting as soon as it became legible. We believe the advantage of color coding was that it eliminated the need to read or even foveate the symbology at all, freeing the pilots to focus their vision and attention on other matters that influence the decision to shoot and thus recognize a good opportunity faster.

Our color code confounded luminance and chromaticity, so our findings cannot be attributed conclusively to chromaticity. For our purposes, this issue is irrelevant because, as we explained earlier, the confound would almost certainly exist in practice, and we wanted to test a realistic case. Nonetheless, we must allow that monochrome luminance coding (with the same luminances as the color code) might have worked as well as the color code. We think this is unlikely, though, because in this case the participants would have had to recognize the symbol luminances as the symbols moved across backgrounds with varying luminances, and humans are not good photometers. The symbol chromaticities, however, were readily recognizable against all the backgrounds, so it is more probable that it was chromaticity that gave the advantage.

Currently we are redesigning the symbol shape and mechanization characteristics to further exploit the apparent advantages of color coding. Our next experiment will compare this new format with the color-coded VCATS symbology reported on here.

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