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LCD Versus CRT Displays: A Comparison of Visual Search Performance for Colored Symbols

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LCD versus CRT Displays: A Comparison of Visual Search Performance for Colored Symbols

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Visual search performance for tactical symbols was examined with liquid-crystal (LCD) and cathode-ray tube (CRT) displays. Twenty-four adult participants (19 men, 5 women; mean age 41 years) searched for navy tactical display symbols on a map background. LCD and CRT displays of similar size and resolution (52 cm diagonal, 1280 × 1024 pixels) were used. Viewing angle (0° vs. 60° of azimuth), set size, target color (blue, red, or white), target presence, and search type (feature vs. conjunction) were also manipulated. Participants showed reduced sensitivity for red and blue symbols viewed 60° off axis with the LCD relative to on-axis LCD, or to the CRT on or off axis. Colored symbols viewed off axis on the LCD produced longer response times in feature search and lower search efficiency in conjunction search. The results argue against the use of current LCD technology when off-axis viewing is likely and color coding is used.

INTRODUCTION

This paper describes an experiment examining the relative effectiveness of two display technologies: a liquid-crystal display (LCD) and a conventional cathode-ray tube (CRT) of similar resolution and size. Within the naval community, there is interest in the use of LCDs on ships because of their lower weight and power consumption, smaller footprint, and lowered susceptibility to electromagnetic interference. This specific interest mirrors a more general consumer interest in LCD technology for desktop computers.

LCD and CRT Technologies

LCDs are composed of many tiny liquid crystals arranged in rows and columns. Liquid crystal molecules can be reoriented by an electric field. LCDs function by twisting the axis of polarization of the light as it passes through the liquid crystal such that when the light reaches the front polarizer, it is oriented correctly to pass through, allowing it to be seen by an observer. When an electric field is applied, the structure is untwisted and no light is emitted (Asian Technology Information Program, 2002). The LCDs used for computer displays are most commonly active matrix, with an electronic switch at each pixel location (Luder, 1997).

In contrast, conventional CRT displays rely on an evacuated glass tube with a display screen at one end and electron guns at the other. The guns emit electron beams that are deflected to various screen locations by use of magnetic fields generated by a deflection yoke. The beams strike phosphors near the screen, converting the electrons to observable light energy. A particular pixel is illuminated or not by coordinating the timing of the gun output and the magnetic fields controlling the deflection yoke.

Given the vastly different technologies underlying each display type, it is no wonder that the images rendered with LCD and CRT displays differ. Among other differences, the pixel definition with LCDs is much sharper than for CRTs (Wright, Bailey, Tuan, & Wacker, 1999). CRTs tend to produce a blurred Gaussian

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distribution of light at each pixel, whereas LCDs produce a sharp edge to each pixel (Menozzi, Napflin, & Krueger, 1999). This sharp edge has clear advantages, but the edge may be problematic when rendering curves (leading to aliasing problems) and may introduce a high spatial frequency noise component into the display.

Viewing angle is an important factor in operational display performance. Photometric measures of angular luminance and chromaticity indicate reduced luminance and color distortion with off-axis viewing orientations on an LCD (Selhuber & Parker, 1997). When viewed off axis, the light takes a longer path through the liquid crystal material and the light receives a greater twist than that from an on-axis position. This results in a drop in luminance for an "on" pixel and an increase in luminance for an "off" pixel. Optical measurements with CRTs indicate that although off-axis luminance and color distortion problems occur, they are less of a problem. However, it is not known whether the off-axis problems with display optics are severe enough to affect human participants performing an operational task. To our knowledge no studies have investigated this question.

The question is important because LCDs have many advantages, as noted, those faced with the decision about whether to purchase LCDs may be interested in knowing about possible limitations of LCD technology. Off-axis viewing is a special problem for display viewing in the naval operations room because it is common for the same display to be viewed by multiple individuals, some of whom are standing to the left or right of the display screen. Business computer users are also accustomed to information sharing on monitors. Displays are getting larger, and the larger the display the more likely it is that an observer will be off axis with respect to some part of the display. Hence it is important to determine whether human performance is degraded by off-axis viewing of LCD and CRT displays.

Human Performance Measurement

Although some studies comparing LCD and CRT technologies have used subjective ratings as a measure of display quality (e.g., Sola, Garner, & Mikulewicz, 1998), relatively little attention has been given to more objective task performance measures. Those studies that have examined human performance with LCDs and CRTs have confounded display technology with other factors, such as display size and pixel resolution (MacKenzie & Riddersma, 1994, Menozzi et al., 1999; Wright et al., 1999).

Specifically, MacKenzie and Riddersma (1994) found a CRT advantage after comparing a 235 × 176 mm (9.3 × 6.9 inch) CRT at 640 × 480 pixels (horizontal × vertical) with a 190 × 120 mm (7.5 × 4.7 inch) LCD at 640 × 200 pixels. Menozzi et al. (1999) found an LCD advantage after comparing a 356 mm (14 inch) diagonal CRT at 800 × 600 pixels with a 264 mm (10.4 inch) diagonal LCD at 640 × 480 pixels. However, display resolution is a likely causal factor. When resolution of these researchers' displays is computed in pixels per inch, the results show that the display type with higher resolution (in at least one dimension) produced better performance.

In a study conducted by Wright et al. (1999), two LCDs with different resolutions (83 and 157 pixels/inch) were compared with a 102 pixels/inch CRT. The Wright et al. results are again consistent with a resolution explanation: Regardless of viewing distance, more words were read when the resolution was increased, with CRT performance sandwiched between that of the two LCD displays. To properly understand whether display type has an effect, display size and pixel resolution should be equated so that pixels per inch is constant across display types.

Visual Search

A visual search task (Nugent, Keating, & Campbell, 1995; Treisman & Gelade, 1980, Wolfe, 1994) serves as an appropriate benchmark for examining human performance with different display types. Visual search is a necessary component task for many naval shipboard operations (Nugent, et al., 1995). In visual search an observer looks for a particular target symbol among many distractors on a display and must indicate whether or not the target is present. Increased response time or error in visual search with a display unit implies that the search process is less effective with that display. Using a signal detection approach (Macmillan & Creelman, 1991), sensitivity and response bias measures can be derived from the error scores to isolate an observer's ability to detect a target (sensitivity) from his or her predisposition toward saying that the target is present (response bias).

In addition, if response time is plotted as a function of the number of symbols on the display (set size), the resulting slope can be used as a metric of processing efficiency. A positive slope implies a limited-capacity (and possibly serial) process (see Wolfe, 1994); a zero slope implies a parallel process. Slopes can be taken as a measure of the processing cost for each additional symbol (Wolfe, 1994). Thus it is important to vary set size in the visual search experiment and to observe its effect on response time.

Visual Search with Monochrome Symbols

Naval tactical displays typically depict a theater of operations with symbols superimposed on a map background. Naval Tactical Display System (NTDS) symbology is used for tactical displays on U.S. and Canadian naval vessels. Some examples are shown in Figure 1. The shape of the symbol codes its identity (friend = circle, hostile = diamond, unknown = square). Contact information is provided by the symbol's orientation (pointing up indicates air, pointing down indicates subsurface, and full symbol indicates surface).

In a recent experiment Hollands, McFadden, Cassidy, and Boothby (2000) had observers search for NTDS symbology displayed on LCD and CRT displays, viewed on and off axis. Set size was also varied. The symbols shown in Figure 1 were displayed in white on a dark background. It was hypothesized that search performance (as measured by response time and the signal detection sensitivity measure *d'*; Macmillan & Creelman, 1991) would deteriorate off axis, especially for the LCD. However, the results showed that although sensitivity decreased with set size, display type and viewing angle had no effect. There was no response time or slope difference between LCDs and CRTs, viewed on or off axis. The search rate (slope of the target-absent function) was about 200 ms per symbol. (As a point of reference, search rates of 40–60 ms per item are considered inefficient in the visual search literature; Wolfe, 1997.)

Thus the Hollands et al. (2000) results showed highly inefficient search for monochrome NTDS symbols, suggesting a serial search process. Of more importance is the fact that no display type or viewing angle effect was obtained. It appears, therefore, that visual search performance was unaffected by display type despite the vastly different display technologies and that the optics of the off-axis LCD did not adversely affect human performance. However, it is possible that certain symbol shapes in their experiment were adversely affected. To investigate this possibility, in the next section we present an analysis of target shape for their data.

TARGET SHAPE ANALYSIS

Hollands et al. (2000) did not report any effects of target shape (circle, diamond, square). We present here an analysis of target shape for their sensitivity and response time data. Data were averaged over target orientation because the number of trials in their experiment was insufficient to allow an analysis on both variables. The intent of the analysis was to determine if target shape affected performance and, especially, if it interacted with display

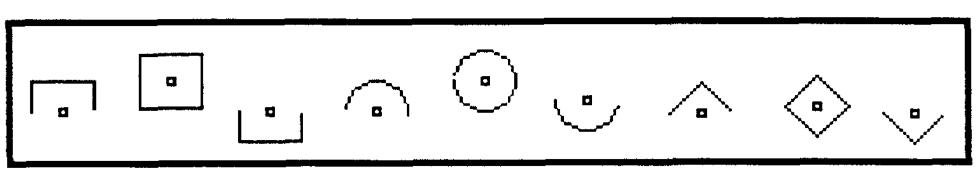

Figure 1. Set of nine NTDS symbols used in experiment.

type, viewing angle, or both. For this reason, only those effects involving target shape and its interactions with display type and viewing angle will be reported here.

Signal Detection Measures

Sensitivity (d') values were computed for each target shape for each of the participants in each experimental condition. These data were submitted to a between/within analysis of variance (ANOVA) with two between-subjects factors (display type and viewing angle) and three within-subject factors (symbol size, set size, and target shape). Sensitivity was greater for square ($M = 2.50$) than for diamond ($M = 2.24$) symbols, with circles ($M = 2.40$) being intermediate, $F(2, 40) = 21.72$, $MSe = 0.117$, $p < .0001$. No other effect reached conventional significance levels ($p > .05$).

Response Time

A mean log response time (RT) was obtained for each target shape for each participant in each experimental condition. These data were submitted to a between/within ANOVA with two between-subjects factors (display type and viewing angle) and four within-subject factors (symbol size, set size, target shape, and target presence). The analysis showed that on the CRT, RTs were shorter for square ($M = 4.25$ s) than for diamond ($M = 5.06$ s) symbols, with the circles ($M = 4.54$ s) being intermediate, but there was no difference among target shapes on the LCD ($M = 4.77$, 4.68, and 4.40 s for diamond, circle, and square, respectively), $F(2, 40) = 4.22$, $MSe = 0.05$, $p < .05$. No other interaction reached conventional significance levels ($p > .05$).

Summary

The analysis revealed a problem for detection of the hostile diamond symbol. However, despite gross changes in the viewing situation, the detectability of a given target shape remained reasonably consistent in the Hollands et al. (2000) experiment, and target shape did not interact with display type and viewing angle. Although there was an interaction between display type and target shape for response time, it showed that the effect of target shape was less for the LCD than for the CRT.

COLOR CODING

Recently it has become more common to code the identity of a symbol redundantly using color on tactical displays (Nugent et al., 1995). Generally, redundant color coding is a useful display technique (Christ, 1975; Space and Naval Warfare Systems Command, 1991; Wickens & Hollands, 2000) and should increase the speed of search. If colored symbols on an LCD are particularly degraded by being viewed off axis (because of reduced luminance), then one might expect less efficient search in that condition despite the unique color coding. However, the reduced luminance may not be sufficient to affect human performance. To address this question, we undertook an examination of colored symbols viewed on and off axis with LCD and CRT displays.

Feature and Conjunction Search with Symbology

Search using a single perceptual dimension is called a *feature search*; a search in which levels of multiple dimensions define the target is referred to as *conjunction search*. Because the relationship between targets and nontargets is contextual and volatile in operational settings (e.g., when an unknown vessel is reclassified as hostile), a target symbol on a tactical display may or may not have a unique property, such as a unique color. Hence both feature and conjunction searches commonly occur in real-world situations.

For our experiment, colors were assigned to levels of identity as follows: red = hostile, blue = friendly, and white = unknown (Nugent et al., 1995). Using this mapping meant that color and shape were redundant dimensions (e.g., a diamond symbol was always red, and a red symbol was always a diamond shape). Because color and shape could not be varied independently with this mapping, conjunction search could not occur using color and shape as the dimensions. However, levels of the contact variable have not been assigned particular color codes, and therefore symbol orientation (pointing up, pointing down, or neutral) could be varied independently of color in conjunction search. For example, an observer could search for a red diamond among distractors

TABLE 1: Average Luminance Levels (cd/m^2) for CRT and LCD at 0° and 60° Viewing Angles

	Viewing Angle			
	0°		60°	
Color	CRT	LCD	CRT	LCD
Blue	9.5	9.5	6.2	3.2
White	40.5	40.1	26.8	10.4
Red	14.1	13.8	9.2	3.7
Dark blue	1.8	2.0	1.2	1.6
Gray	3.6	3.7	2.3	2.0

that include other red symbols varying in orientation (pointing up, pointing down).

Synopsis of Experiment

In our experiment, participants searched for red, blue, and white tactical symbols displayed on state-of-the-art LCD and CRT displays of the same size and resolution. We examined a simple feature search situation in which a target had a unique color and a more complex conjunction search situation in which it did not. Viewing angle was manipulated (0° and 60° of azimuth). To assess processing efficiency, we varied set size and target presence. Response time and error measures were obtained, and sensitivity and response bias scores were derived from the error measures.

METHOD

Participants

The study was conducted at Computing Devices Canada (Ottawa, Ontario), and the 24 participants (19 men, 5 women, mean age 41 years) were employees of that company. Participants were recruited by a broadcast e-mail. Participants had normal or corrected-to-normal vision and were screened for color vision.

Apparatus and Stimuli

The two display types were a prototype flat-panel active-matrix in-plane switch LCD in development by Computing Devices Canada (now General Dynamics Canada) and a Sun Microsystems GDM-20E20 CRT. Both displays were approximately 52 cm (20.5 inches) measured diagonally and had 1280 × 1024 pixel resolution at 0.31 mm dot pitch. The resolution of both display types was therefore about 80 pixels/inch (horizontal and vertical). The displays were controlled by a Sun workstation. A chin rest was used to keep the participant's head stationary. The viewing distance was kept constant at 50 cm for both display types and both viewing angles. The experiment was conducted in a dark room (i.e., there was no artificial light source other than the monitor and virtually no natural light in the room).

The symbols shown on each trial were members of the set of nine NTDS symbols shown in Figure 1 (Nugent et al., 1995). Symbols were shown on a map background. Colors (as designated by the X-Window system) for the map/background were "gray25" (a dark gray approximately 25% of the way between black and white) for land and "dark slate blue" for water. Diamond symbols (hostile) were red, circle symbols (friend) were blue, and square symbols (unknown) were white. The blue circle symbols were discriminable from the dark blue background on visual inspection. The symbol size was 19 × 19 pixels.

Light gun levels for each display were manipulated to equalize color patch luminance and chromaticity values across display types for each color (for on-axis viewing). Luminance levels and chromaticity values were collected using a Minolta Chroma Meter CS-100, and Table 1 shows the obtained luminance levels. For the CRT, on-axis chromaticity values (x, y) were .290, .306 (white); .586, .346 (red), and .167, .136 (blue). For the LCD, the values were .289, .307 (white); .585, .349 (red), and .170, .140 (blue).

Design

The experiment had a 2 (display type) × 2 (viewing angle) × 3 (target color) × 2 (search type) × 3 (set size) × 2 (target presence) between/within design, with the first two factors manipulated between subjects and the last four manipulated within subjects. The two viewing angles were 0° and 60° of azimuth (i.e., the display was rotated about its vertical axis 60° so that the screen was angled relative to the participant's head in the chin rest). The three set sizes (i.e., total number of symbols shown during a trial) were 10, 30, and 50. The levels of target color were red, blue, and white (and were uniquely assigned to symbol shape). The levels of search type were feature and conjunction. In feature search, the target symbol was the only symbol of that color (and shape). In conjunction search, there were other symbols the same color as the target, although they differed in orientation.

Each of the six conditions defined by the factorial combination of target color and search type was defined as a block of trials. The order of the six blocks was determined by participant number using a Latin square. The order of trials within a block was randomized. There were 18 trials for each of the three levels of set size, for a total of 54 trials per block. For each level of set size, each of the three NTDS symbols for a given target color/identity was shown as a target three times, producing nine target-present trials. On the other nine trials – target-absent trials – there was no target in the set. For feature search, the distractor symbols were sampled with replacement from the set of six symbols that did not share the target's color (identity). For conjunction search, distractor symbols were sampled from the set of nine symbols minus the target symbol.

Procedure

Each participant was randomly assigned to a condition determined by particular levels of the between-subjects factors and to a particular order of the six blocks. Participants filled out a consent form and were screened for color vision using pseudoisochromatic plates from the Hardy, Rand and Ritter (HRR) test in daylight. In the instructions, participants were told that they would first see a target symbol and, when they had familiarized themselves with the target, that they should press a key to see a set of randomly arranged symbols. They were told that their task was to determine if the target symbol was in the set.

Participants performed six practice trials, one trial representing each of the six blocks, using a set size of 30. Then they proceeded through the experimental trials. On each trial the target symbol was shown, the participant pressed a key when ready, and the symbol set was displayed. This display was shown until the participant responded "present" or "absent," whereupon the next trial commenced. Participants pressed the *1* key on the numeric keypad (labeled with a *P*) for "target present" and the *2* key on the numeric keypad (labeled with an *A*) for "target absent." They kept their fingers directly over the response keys during the experiment. The participant's response and the response time (to the nearest millisecond) were recorded. It took the participants an average of 75 min to complete the procedure. After completion, each received a written debriefing form, filled out a questionnaire, and discussed the experiment with the experimenter.

The questionnaire contained four Likert rating scale items: clarity ("How clearly could you see the symbols?" 1 = *very clearly*, 7 = *not clearly at all*); confidence ("How certain were you that you were making accurate judgments?" 1 = *very certain*, 7 = *not certain at all*), display quality ("In general, how would you evaluate display quality?" 1 = *excellent*, 7 = *poor*), and perceived eyestrain ("Did you experience any eyestrain?" 1 = *no eyestrain*, 7 = *a lot of eyestrain*).

RESULTS

Search Type

A mean response time was computed for each participant in each experimental condition. A logarithmic transformation was applied to the data in order to correct for observed heterogeneity of variance. These means were submitted to a between/within ANOVA with two between-subjects factors (display type and

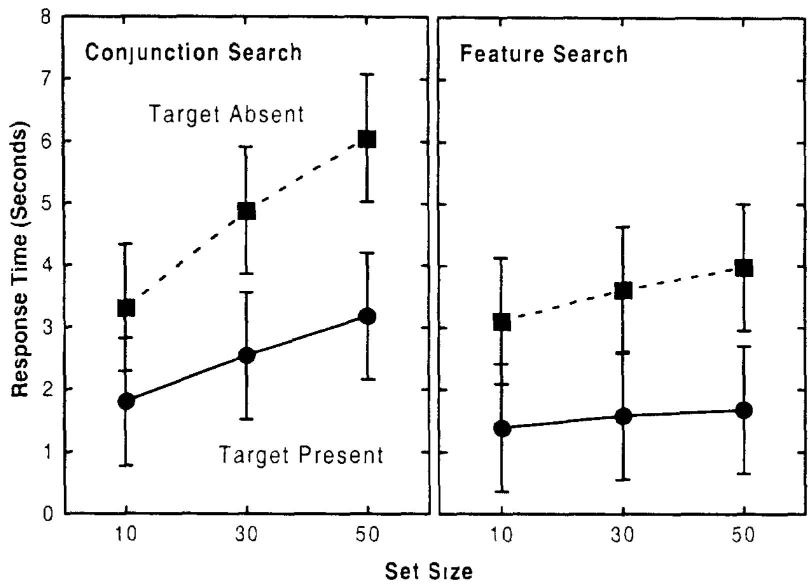

Figure 2. Response time as a function of search type, set size, and target presence. Error bars indicate the standard error of the mean for all graphs.

viewing angle) and four within-subjects factors (target color, search type, set size, and target presence). An interaction among search type, set size, and target presence was found, and the means are depicted in Figure 2.

As predicted, response times were longer and increased more with set size in conjunction search than in feature search, $F(2, 40) = 3.29$, $MSe = 0.004$, $p < .05$. The mean search rate (slope of target-absent function) was greater for conjunction search than for feature search (83 vs. 23 ms per symbol, respectively), $t(23) = 11.95$, $p < .0001$. We therefore treat feature and conjunction searches separately in subsequent analyses for each variable.

Feature Search

Signal detection measures. A mean sensitivity (d') and response bias (β) score was computed for each feature search condition and participant. These scores were submitted to separate between/within ANOVAs with two between-subjects factors (display type and viewing angle) and two within-subjects factors (target color and set size). Participants showed greater sensitivity to white targets than to red or blue targets with the off-axis LCD, but target color had no effect for on-axis LCD or for either viewing angle with the CRT, as shown in Figure 3, $F(2, 40) = 14.93$, $MSe = 0.089$, $p < .0001$. The response bias results showed that participants were more conservative (that is, they were biased against saying "target present") with red and blue targets than with white targets for the off-axis LCD, but target color had little effect on response bias for the CRT whether it was viewed on or off axis, $F(2, 40) = 16.05$, $MSe = 0.259$, $p < .0001$. This pattern is shown in Figure 4.

Response time. Mean log response times were submitted to a between/within ANOVA with two between-subjects factors (display type and viewing angle) and three within-subjects factors (target color, set size, and target presence). Because we conducted a separate regression analysis on slope values, which is described later, effects involving set size are not discussed here. For the LCD, red and blue symbols ($M = 2.78$ and 2.67 s, respectively) required more time than did white symbols ($M = 1.73$ s), but for the CRT, target color had no effect ($M = 1.69$, 1.81, and 1.68 s for red, blue, and white, respectively), $F(2, 40) = 20.31$, $MSe = 0.020$, $p < .0001$. Red and blue symbols required more time when viewed off axis than when viewed on axis ($M = 2.55$ and 2.61 s vs. 1.83 and 1.86 s for red and blue, respectively), whereas viewing angle had little

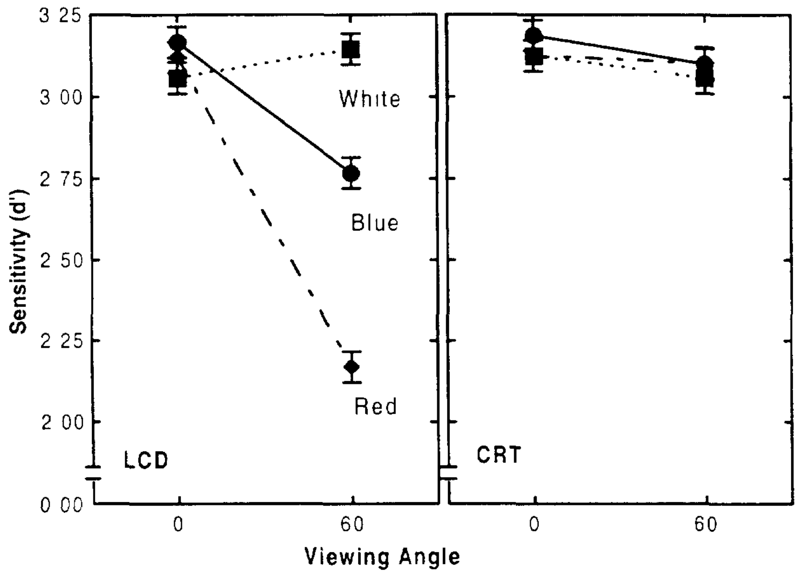

Figure 3 Feature search Sensitivity (d') as a function of display type, viewing angle and target color

effect for white symbols (M = 1 74 s off axis vs 1 67 s on axis), $F(2, 40) = 10.15$, MSe = 0.020, $p <$ 0005

Each participant's target-present response times were regressed over set size for each target color Regression slope values were submitted to a between/within ANOVA with two between-subjects factors (display type and viewing angle) and one within-subjects factor (target color) Viewed off axis on the LCD, blue and red symbols produced greater RT slopes than did white symbols, but target color had no effect on slopes with the LCD viewed on axis or with the CRT from either viewing angle, $F(2, 40)$ = 5 07, MSe = 78 61 $p <$ 05 Mean values are shown in Figure 5 In other

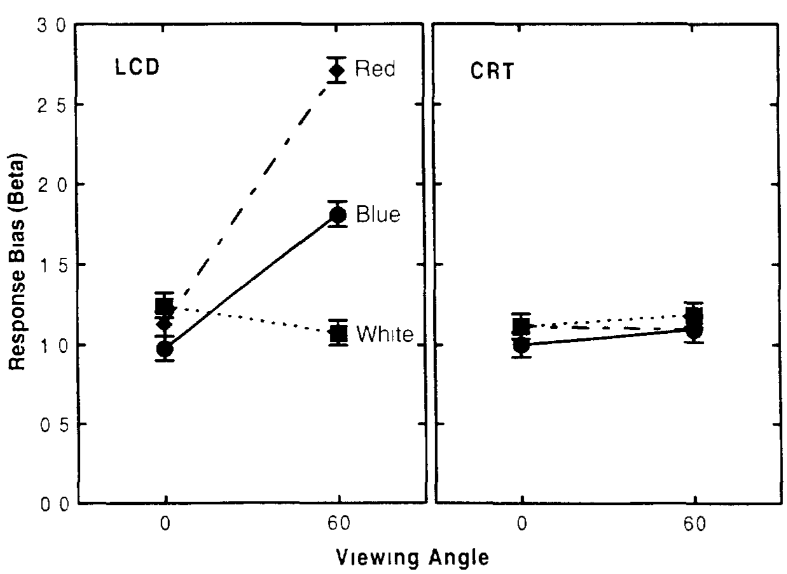

Figure 4 Feature search Response bias (β) as a function of display type viewing angle, and target color

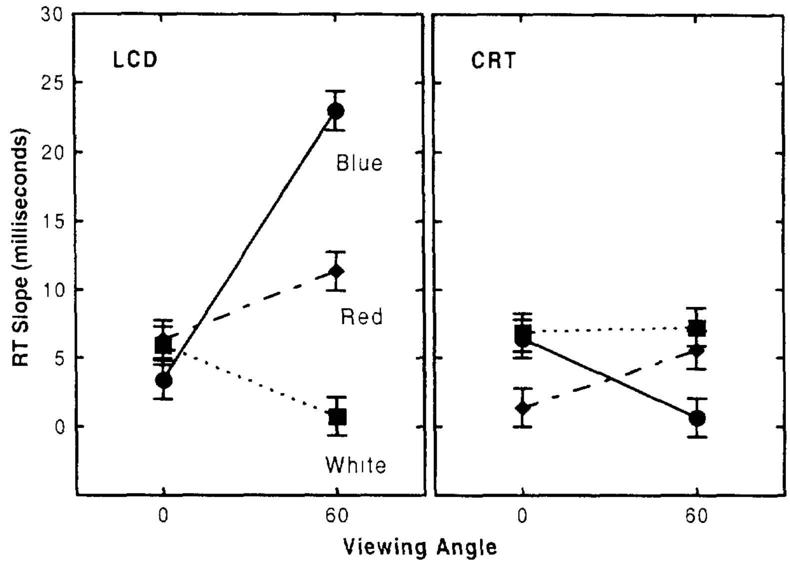

Figure 5. Feature search. Response time slopes as a function of display type, viewing angle, and target color.

words, off-axis viewing made search for colored symbols less efficient for the LCD but had a negligible effect on search efficiency for the CRT.

Conjunction Search

Signal detection measures. As for feature search, mean sensitivity and response bias scores were computed and submitted to separate ANOVAs. Sensitivity was lower for colored targets viewed off axis on the LCD but was only minimally affected by viewing angle for the CRT, $F(2, 40) = 3.319$, $MSe = 0.145$, $p < .05$. The means are shown in Figure 6.

Participants demonstrated a conservative response bias when searching for red and blue targets ($M = 1.69$ and 1.57, respectively), as

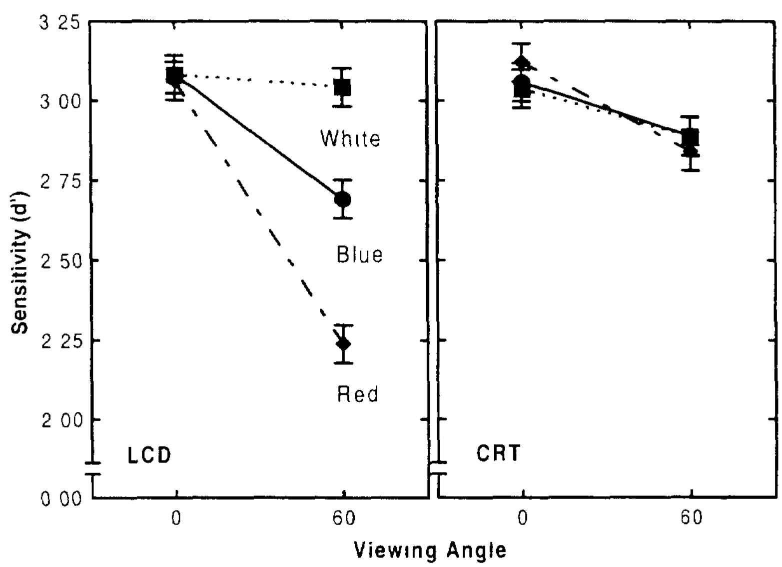

Figure 6. Conjunction search. Sensitivity (d') as a function of display type, viewing angle, and target color.

compared with white targets ($M = 1.12$) on the LCD or any target color on the CRT ($M = 1.27$, 1.12, and 1.31 for red, blue, and white, respectively), $F(2, 40) = 5.19$, $MSe = 0.4358$, $p < .01$. Participants were more conservative with the LCD viewed off axis ($M = 1.80$) than with the LCD on axis ($M = 1.14$) or with the CRT from either viewing angle ($M = 1.27$ and 1.20 for off axis and on axis, respectively), $F(1, 20) = 5.15$, $MSe = 0.8536$, $p < .05$. Participants were more conservative searching for red and blue symbols off-axis ($M = 1.81$ and 1.50, respectively) than when searching for white symbols ($M = 1.26$), but there was virtually no change in response bias with target color for symbols viewed on axis ($M = 1.15$, 1.19, and 1.17 for red, blue, and white, respectively), $F(2, 40) = 3.39$, $MSe = 0.4358$, $p < .05$.

Response time. As for feature search, mean log response times were submitted to a between/within ANOVA. Participants responded more slowly to blue and red targets ($M = 3.76$ and 3.51 s, respectively) than to white targets ($M = 2.53$ s) on the LCD, whereas target color had little effect on response time for the CRT display ($M = 2.76$, 2.75, and 2.44 for blue, red, and white targets, respectively), $F(2, 40) = 11.51$, $MSe = 0.012$, $p < .01$.

Target-present response time slopes were calculated as for feature search data. The slopes were submitted to a between/within ANOVA, which showed that blue symbols produced greater RT slopes ($M = 46$ ms per symbol) than did red and white symbols ($M = 25$ and 17 ms per symbol, respectively) for the LCD but target color had little effect on slopes for the CRT ($M = 23$, 27, and 26 ms per symbol for blue, white, and red, respectively), $F(2, 40) = 6.20$, $MSe = 269.86$, $p < .005$. The analysis also showed that slopes were greater for off-axis than for on-axis viewing ($M = 23$ vs. 32 ms per symbol, respectively), $F(1, 20) = 5.33$, $MSe = 271.36$, $p < .05$.

Subjective measures. Four subjective measures were collected from each participant (clarity, confidence, display quality, and perceived eyestrain). Data for each measure were submitted to a separate 2 × 2 (Display Type × Viewing Angle) between-subjects ANOVA. No result reached conventional significance levels ($p > .05$ in each case).

DISCUSSION

Participants were less able to detect colored targets viewed off axis on the LCD. This was true for simple feature search and for more complex conjunction search. In addition, for feature search, participants took longer to detect the colored target with off-axis LCDs. Moreover, they were biased against calling the target present, demonstrating a conservative response bias. For feature search, colored targets viewed off axis on the LCD produced lower search efficiency.

The target shape analysis conducted on the Hollands et al. (2000) data showed that the diamond symbol was more difficult to detect than were the other symbols and that they also took longer to detect on the CRT. These problems disappeared in the current experiment, in which performance with the red diamond symbol was generally as good as for the other symbols, except in the off-axis condition with the LCD. The implication is that color coding aided the detection of diamond-shaped symbols for the CRT and on-axis LCD. However, an experiment that orthogonally manipulated target shape and color would be necessary to clarify the exact contribution of each factor.

The results therefore highlight a problem for conventional LCD technology. Although 60° is a relatively extreme viewing angle, it was only in the horizontal viewing direction (azimuth). Reduced luminance and color distortion can occur at smaller angles when the display is viewed off axis in both horizontal and vertical directions. Given the trend toward larger displays, an observer is nearly always off axis with respect to part of the display. Thus viewing angle will become of greater concern as larger displays become more common.

The naval community is interested in using LCD technology to display tactical information on ships. If tactical information is interpreted by multiple individuals sharing a common display, they cannot all simultaneously view the tactical information on axis. In addition, the naval community has an interest in using color to code information on tactical displays. The current results suggest that these mutual interests may be problematic. Thus the problem for LCD manufacturers is to improve that display technology to afford better off-axis viewing of colored symbols. In particular, given our photometric measurements, the problem appears to be the reduced luminance of LCD pixels viewed off axis. Techniques that increase the off-axis luminance emitted from a pixel have recently been developed to deal with this problem (e.g., NEC XtraView, NEC Corporation, Tokyo, Japan). This may help address the off-axis problem observed in this study.

Not surprisingly, feature search was more efficient than conjunction search. However, both feature and conjunction search rates were generally faster (i.e., more efficient) than the rate obtained by Hollands et al. (2000) with white symbols. In the current experiment, the target absent search rate for feature search was about 25 ms/item, and the rate for conjunction search was 83 ms/item. Hollands et al. obtained a rate of 200 ms/item. Presumably the use of redundant color coding increased search efficiency.

Any study comparing different display technologies is to some degree limited to the particular technology tested. The LCD panel used in this experiment was state-of-the-art technology at the time the study was conducted. However, given the rapid advances in display technology, the results cannot be interpreted as a general criticism of LCD technology; rather, they highlight specific problems with existing technology that can be addressed by technological innovation. We think it is important to continue to test advances in display technology in tasks that reflect components of real-world activities. Only in this way can it be determined whether technological advances are in fact advances for the human-machine system.

Design Implications

The results have the following implications for display design. First, the use of CRT technology is encouraged for situations in which off-axis viewing is likely and color coding is used. Second, the development of LCD technology that increases the off-axis luminance for red and blue pixels, or that otherwise improves off-axis chromaticity, is encouraged. Finally, the use of redundant color coding with shape is recommended in situations in which an observer searches for an iconic symbol on a display and will also help in the detection of the diamond symbol shape with CRTs and with LCDs viewed on-axis.

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