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Identification of Text and Symbols on a Liquid Crystal Display Part II: Contrast and Luminance Settings to Optimise Legibility

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ABSTRACT

This study aimed to identify the luminance and contrast levels necessary to minimise the threshold identification size of bright letters displayed over a dark background on an LCD under low (1.5 lux) and high (260 lux) lighting conditions. White, pure red, pure green and pure blue upper-case Bailey Lovie letters with a contrast between 3:1 and 300:1 were displayed on an LCD to 20 participants. The threshold identification size was equivalent for all colours except for blue, which had larger threshold identification size than white, red and green at all character luminance levels tested. The threshold identification size initially decreased as character luminance increased, but asymptoted to a minimum size after which further increases in character luminance yielded no additional significant reduction in the threshold identification size. The threshold identification size was relatively insensitive to contrast provided the contrast level was above 6:1. Self-report preferred character luminance levels were generally higher than the character luminance levels necessary to achieve minimum threshold identification size. It is recommended that character luminance should be approximately 20 cd / m2 under dark lighting conditions and approximately 60 cd / m2 under bright lighting conditions. These values translate to contrast levels of 20:1 and 60:1 under the suggested screen background luminance of 1.0 cd / m2.

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Executive Summary

The Royal Australian Navy (RAN) ANZAC Class Frigates will be upgraded with an enhanced Anti-Ship Missile Defence (ASMD) capability. The upgrade involves the development of a new Combat Management System (CMS) that will use liquid crystal displays (LCDs). The legibility of text and symbols displayed on an LCD will be dependent upon their contrast and luminance, and may also depend on colour. If the contrast and luminance levels are poorly adjusted, text and symbol sizes may need to be larger than if optimal settings are used. This study aimed to identify the contrast and screen luminance settings that minimise the threshold identification size for white, primary red, primary green and primary blue letters displayed on an LCD similar to that planned for use in the ASMD CMS when viewed under the ambient light levels experienced in ANZAC operations rooms. The results should be directly applicable to the ASMD upgrade project as well as to LCDs generally.

The twenty DSTO volunteers who participated in the study attempted to identify white, pure red, pure green and pure blue letters presented on the LCD with contrast levels ranging between 3:1 and 300:1. Participants viewed the letters under low and high ambient lighting conditions comparable to the levels experienced in ANZAC ops rooms. Two screen-background luminance levels were used in the dark lighting condition: 0.2 cd / m^2, which was the minimum uniform luminance that can be achieved at the minimum LCD backlight brightness setting, and 1.0 cd / m^2, which is the minimum uniform luminance that can be achieved at the maximum backlight brightness setting.

Threshold identification size was equivalent for white, primary red and primary green characters at all contrast levels, but primary blue had a larger threshold identification size than the other colours. In addition, the LCD could not produce pure blue at high character luminance levels, thus it is recommended that pure blue not be used in the ASMD CMS. Cyan (an equal combination of blue and green) may be an acceptable alternative, as proposed by MIL-STD-2525B.

The threshold identification size initially decreased as contrast increased, but asymptoted to a minimum level after which further increases in contrast yielded no additional significant reduction in threshold identification size. The threshold identification size was relatively insensitive to contrast, provided the contrast level was above 6:1. It is therefore suggested that contrast levels should be greater than 6:1. Self-report preferred character luminance levels were generally higher than the character luminance levels necessary to achieve minimum threshold identification size and it is recommended that text luminance be approximatley 20 cd / m^2 under dark lighting conditions and approximately 60 cd / m^2 under bright lighting conditions. This translates into contrast levels of 20:1 and 60:1 respectively under the suggested screen background luminance of 1.0 cd / m^2.

Authors

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Kingsley Fletcher joined DSTO in 2006, having previously worked in telecommunications engineering. He received a Bachelor of Health Science (Hons) in Psychology from the University of Adelaide in 2005, a Master of Business Administration from the University of Adelaide in 1993 and a Bachelor of Engineering (Hons) from the University of Adelaide in 1986. He currently works in the Human Factors Discipline of the Maritime Operations Division, focusing on human-machine interactions in the combat operations rooms of surface ships.

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Stuart holds an honours degree in Electronic Engineering from the University of Sussex and a Graduate Certificate in Human Factors from the University of Queensland. He began his career designing and building computerised electronics for the theatre. Following this he worked on sensor signal processing, tracking and fusion for military optoelectronic sensors and on the assessment of naval platform vulnerability to optical detection. Recent work includes the assessment of networked naval gunfire support, ergonomic assessments of combat system consoles and seating, advice on operations room design for the RAN's ANZAC ships and running the first ANZAC SEA WARRIOR exercise.

Karen Nugent
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Karen Nugent joined the Maritime Operations Division at DSTO in 2006, as a graduate after receiving a Bachelor Information Technology from the University of Queensland in 2004. Prior to this she was an Architect, having received a Bachelor of Architecture (Hons) from the University of Queensland in 1999 and obtaining registration with the Board of Architects of Queensland in 2005. She now works for the Command Control Communications and Intelligence Division, developing software to improve situational awareness in command and control applications.

Contents

1. Introduction

The Royal Australian Navy (RAN) ANZAC Class Frigates are being upgraded with an enhanced Anti-Ship Missile Defence (ASMD) capability. The upgrade involves the development of a new Combat Management System (CMS), which integrates the war fighting capability of a ship by displaying information derived from sensors, such as radar and sonar, on computer screens and allows the control of weapons. As long as good display principles are followed and the limits of human cognitive processing are recognised, the display of additional information on CMS screens can lead to increased situational awareness and better decision making. Thus, there is often a desire to maximise the information available to the user on each screen. Reducing the font size is one method of increasing data density, however, if the font size becomes too small, reading speed and accuracy will deteriorate. Thus one aspect of the design of the new CMS is to identify how small text and symbols can be made without impacting upon readability.

The ability to identify text and symbols displayed on a computer screen will be influenced by their size, luminance, luminance contrast and possibly their colour. If luminance and luminance contrast are not appropriate for the ambient light conditions, text and symbol sizes may need to be larger than if optimal settings are used. Thus, identification of optimal contrast and luminance settings is necessary prior to determining text and symbol size thresholds. The current study aims to determine the luminance and luminance contrast levels that minimise the threshold size for letter identification of characters displayed on a modern, high resolution Liquid Crystal Display similar to that proposed for use in the CMS.

Sufficient luminance contrast is necessary to detect and identify visual stimuli. Detection and identification performance improves rapidly with increasing contrast at low contrast levels, but becomes nearly independent of contrast once a threshold contrast level is reached (Blackwell, 1946). The threshold luminance contrast level depends on the size of the visual stimuli, with smaller stimuli requiring a higher luminance contrast than larger stimuli. (Blackwell, 1946; Legge, Rubin, & Luebker, 1987; Nasanen, Ojanpaa, & Kojo, 2001) Thus, the luminance contrast necessary to minimise the threshold letter identification size is also likely to be sufficient to maintain identification and reading performance for larger text sizes, and it can be used as a minimum luminance contrast level in the design of displays regardless of the displayed character size.

The ability to identify visual stimuli also increases with the luminance level to which the eye is adapted (Blackwell, 1946; Legge, Pelli, Rubin, & Schleske, 1985; Shlaer, 1937). In situations where there is one main fixation point, the average luminance within about 20 degrees of the fixation point is considered to be a reasonable estimate of the adaptation luminance level (Boyce, 2003). This is larger than the visual angle subtended by even a 30” computer screen at a typical viewing distance of 650 mm; thus the luminance of the characters displayed on the computer screen, the screen-background luminance and the luminance of the area immediately surrounding the computer screen letter may jointly influence identification performance. The luminance of the area surrounding the computer screen will be affected by the level of ambient illumination, and this study examined letter identification performance under both low and high ambient light conditions, which could be expected to produce different levels of luminance adaptation. The ambient light conditions were chosen to be typical of dark and bright naval operations room lighting.

Military systems often use negative polarity displays, where bright characters are displayed on a dark background, in order to preserve dark adaptation in low-light environments. Negative polarity displays are not commonly used in high ambient light conditions, and few studies exist that can be used for design guidance. The display polarity does not appear to have a large effect on the threshold luminance contrast (Legge et al., 1987; Ojanpaa & Nasanen, 2003), but the low screen-background luminance may mean that character luminance is an important contributing factor to the adaptation luminance level, particularly in low ambient light conditions. Mourant and Langolf (1976) examined the minimum luminance levels necessary for automobile controls under night driving conditions, but the age range of their sample (between 45 and 67) limits the application of their results to military environments, where the age range is typically between 17 and 40 years.

The eye is not equally sensitive to all wavelengths and it might be expected that text colour would affect readability and legibility although this may not be the case if each colour is matched for photopic luminance. This possibility is supported by Matthews, Lovasik, and Mertins (1989), who found that colour had a minimal effect on visual search performance when the luminance of each colour was adjusted for equal perceived brightness. However, colour discrimination decreases under low luminance levels (Legge, Parish, Luebker, & Wurm, 1990), and monochromatic acuity is worse than achromatic acuity (Chen & Yu, 1996; Legge et al., 1990). Thus white and coloured text may have different legibility under low and high ambient light conditions.

In addition to white characters, military displays typically use red, green and blue, which are the primary colours in most LCDs, to colour-code text and tactical symbols. Blue text can have low legibility when displayed on a black background and, in general, is avoided in display designs. However blue is an important colour in military displays, and newer LCDs may have mitigated this problem by altering the chromaticity of the blue primary (Arend, Logan, & Havin, 2005). Thus the current study used primary red, green and blue in addition to white (equal red, green and blue (RGB) levels), with the RGB levels of each colour adjusted to produce equal photopic luminance.

When designing and evaluating computer visual displays, it is important to consider effectiveness, efficiency and satisfaction (ISO, 1998). Effectiveness and efficiency can often best be captured by objective measures, such as the threshold letter identification size used in the current study, but self report measures are needed to capture user satisfaction or comfort, which can be an important consideration when displays have to be used for long periods of time. It is not sufficient to assume that conditions that induce optimal objective performance will produce optimal satisfaction and comfort (Boschman & Roufs, 1997), and thus the current study also measured the character luminance levels preferred for ease and comfort of reading.

The current study aims to identify the contrast level that optimised legibility and self-reported preferred contrast level for reading white, primary red, primary green and primary blue letters of equal photopic luminance when displayed on an LCD under three viewing conditions:

1) Low ambient lighting (1.5 lux) with a screen background luminance of 0.2 cd / m^2, which was the lowest uniform screen background luminance that could be achieved with the LCD set to minimum brightness (Fletcher & Sutherland, 2009),
2) Low ambient lighting with a screen background luminance of 1.0 cd / m^2 and
3) High ambient lighting (260 lux) with a screen background luminance of 1.0 cd / m^2, which was the minimum uniform luminance achievable with the LCD set to maximum brightness.

The study used an LCD that is similar to that intended for use in the ANZAC ASMD CMS consoles, and used ambient light levels equivalent to those of the actual ANZAC operations rooms. This level of fidelity should allow firm recommendations to be made on the contrast level and brightness levels that should be used in the ASMD CMS displays. The results of the study will also be used in a subsequent study that aims to identify the minimum text and symbol size that allows fast and accurate identification performance (Fletcher, Sutherland, Nugent, & Grech, 2009).

2. Method

2.1 Design

The study was conducted under two ambient light conditions: low (1.5 lux) and high (260 lux). Incandescent globes generated the low ambient light level with a CIE colour coordinate of (.515, .445). Fluorescent lights generated the high ambient light level with a CIE colour coordinate of (.414, .450). Given that military operations rooms run under low ambient lighting in order to maintain maximum dark adaptation for personnel moving between the room and other compartments, the LCD was set at its minimum backlight brightness setting for the low light condition. Under high ambient lighting, the LCD was set at its maximum backlight brightness setting in order to maximise the screen luminance capability. There was a large difference in the character luminance range achievable at each brightness level, thus different character luminance levels were chosen for each ambient light condition. A dark screen background was required to maintain dark adaptation and, as 1.0 cd / m^2 was the minimum uniform luminance achievable with the LCD set to maximum brightness, this was used as a common screen background luminance for both ambient light conditions. A second screen background luminance of 0.2 cd / m^2 was used in the low ambient light condition as this was the minimum uniform luminance that could be achieved with the LCD set to minimum brightness. Both ambient light conditions used the same participants, but the high ambient light condition was tested approximately two weeks after the low ambient light condition tests due to constraints on the availability of stimuli.

2.2 Participants

Twenty volunteers employed at the Defence Science and Technology Organisation (DSTO), Australia, participated in the study. Their ages ranged from 20 to 41 years, (Mean (M) = 30.90 years, Standard Deviation (SD) = 7.79 years). There were equal numbers of males and females. All participants had normal colour vision, as tested by the 12 plate Ishihara colour vision test, and 6 / 6 or better corrected binocular visual acuity, as tested using far and near point optical charts.

2.3 Apparatus

An Apple M9179LL / A 30" LCD monitor with a native resolution of 2560 x 1600 pixels at 60 Hz was used to display all experimental stimuli. This was driven by a Hewlett Packard desktop computer with a P4, 3.6 GHz processor, 1 Gb of RAM and a NVIDIA GeForce 7800 GTX 256 MB dual-link DVI video card capable of driving the LCD at its native resolution. The system software was Windows® XP with the ClearType feature disabled in order to eliminate possible stimulus luminance non-uniformity caused by font-smoothing and anti-aliasing. Custom software was written to control the stimulus presentation using Java RE 6.0 and PXLab 2.1.6. A chin and forehead rest was used to maintain a constant viewing distance from the screen. A Tectronix J17 photometer with a J1803 luminance sensor head was used to collect luminance measurements. An Ocean Optics S2000 Spectrometer was used to measure spectral density from which CIE 1964 colour coordinates were calculated (Wyszecki & Stiles, 1982).

2.4 Stimuli

The stimuli used to measure identification performance consisted of the upper-case letters D, E, F, H, N, P, R, U, V and Z, which were adopted for visual acuity testing by the British Standards Institution (BSI, 1968). The letters were rendered in Verdana font and were surrounded by eight flanking characters comprised of the superposition of the O, X and + characters. An example of an identification stimulus is shown in Figure 1. It is more difficult to identify characters when other characters are closely adjacent than when presented alone (Flom, Weymouth, & Kahneman, 1963) and, as reading typically involves words of more than one letter, the flanking characters were included in order to incorporate any effects of crowding on identification. Crowding is thought to be caused by the visual integration of shape features within the visual field (Pelli, Palomares, & Majaj, 2004), and the flanking characters were designed to incorporate the letter shape features present in Verdana capital letters, namely horizontal lines, vertical lines, diagonal lines and curved lines. The flanking characters were used to provide a more consistent crowding effect than what might have been achieved using specific letters.

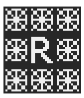

Figure 1: Example of a crowded white visual acuity letter stimulus

The letters and flanking characters subtended visual angles (in minutes) of 3.2 min, 4.0 min, 5.0 min, 6.3 min, 7.9 min and 10.0 min at a viewing distance of 2720 mm. At this viewing distance the letters had at least 10 vertical pixels, which avoided confounding the effects of visual angle and the number of pixels on legibility (Sheedy, Subbaram, Zimmerman, & Hayes, 2005). Successful identification of a 5 min high letter implies the ability to resolve letters with a line width of 1 min and equates to a threshold identification size score of 0 in log (min) units. The letter heights differed by 0.1 log (min) and thus represent log (min) acuity scores of -0.2, -0.1, 0.0, 0.1, 0.2 and 0.3 (Bailey & Lovie, 1976).

The luminance of white characters spanned a range between 0.2 cd / m^2 and 69 cd / m^2 at the minimum backlight brightness, and between 1.0 cd / m^2 and 288 cd / m^2 at the maximum backlight brightness. The LCD was unable to produce all levels of luminance for red, green or blue, and the character luminance levels used for each colour under both ambient lighting conditions are shown in Table 1. The CIE colour coordinates for white, red, green and blue were (0.336, 0.414), (0.636, 0.352), (0.315, 0.610) and (0.137, 0.160) respectively, which were stable over the range of luminance levels tested. The luminance data for the high ambient light condition incorporates the result that screen reflections from the room lighting increased the character and screen background luminance by 0.5 cd / m^2. The ambient lighting also caused the visible surfaces surrounding the LCD to have an average luminance of 19 cd / m^2. The character luminance was not measured from the actual stimuli, but instead was measured using solid blocks with RGB levels that matched those used in the character stimuli. Since it is possible for large and small characters with identical RGB levels to have different luminance levels, the luminance of solid block and checkerboard patterns with the same number of bright and dark pixels were measured and found to be identical. This indicated that the luminance of a particular RGB level was independent of the size of the character displayed.

Table 1: Character luminance levels used for each colour under each viewing condition

High Ambient Light (260 lux)					
Screen-Background Luminance 1.5 cd/m2					
Color	**Character Luminance (cd/m2)**				
White	15.5	25.5	60.5	150.5	280.5
Green	15.5	25.5	60.5	150.5	-
Red	15.5	25.5	60.5	-	-
Blue	15.5	25.5	-	-	-
Low Ambient Light (1.5 lux)					
Screen-Background Luminance 0.2 cd/m2 & 1.0 cd/m2					
Color	**Character Luminance (cd / m2)**				
White	3	6	15	30	60
Green	3	6	15	30	-
Red	3	6	15	-	-
Blue	3	6	-	-	-

Displaying a uniform RGB level on the LCD did not result in a uniform luminance across the screen, and this non-uniformity was reduced by adjusting the RGB values of the screen-background image. Measurements taken at 40 uniformly spaced screen points revealed that, at the minimum LCD brightness, the luminance uniformity adjustments produced a corrected mean luminance of 0.21 cd / m^2 (SD = 0.02 cd / m^2) and 0.98 cd / m^2 (SD = 0.03 cd / m^2) for the two screen background luminance conditions. At the maximum LCD brightness the corrected mean luminance was 0.97 cd / m^2 (SD = 0.06 cd / m^2) (Fletcher & Sutherland, 2009).

Four stimuli were used to measure self-report preferred luminance in each ambient light condition, one for each colour. The preference stimuli consisted of between two and five rows, each row consisting of all ten 5.0 min (0 log (min)) legibility stimuli arranged horizontally. 5.0 min letters were chosen as this was the smallest letter size that participants were expected to resolve, thus providing a test for the most difficult reading condition. Each line displayed the stimuli at one of the luminance levels tested at that colour, thus the white preference stimuli had five lines, the green screen four lines, the red screen three lines and the blue screen two lines. The luminance of each line increased from top to bottom, and a vertical separation of three line heights was used between each line. An example of a preference stimulus is shown in Figure 2.

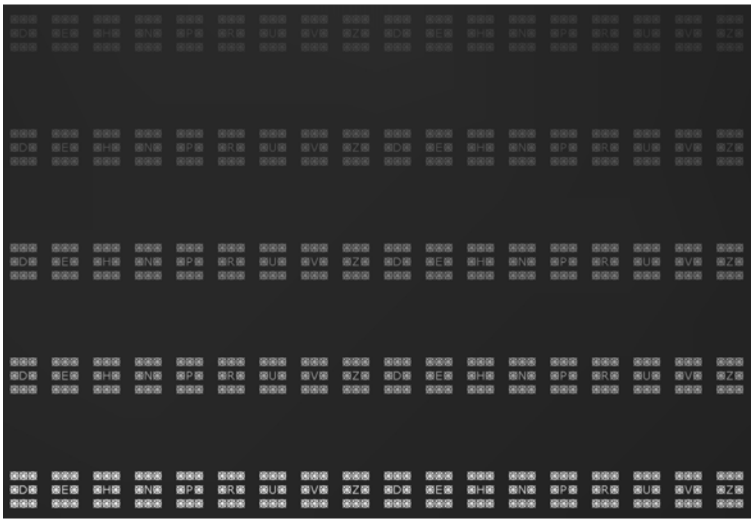

Figure 2: Example of the white preference stimulus

2.5 Procedure

The stimuli used to measure identification performance were presented individually at the centre of the LCD. Participants viewed the screen at a distance of 2720 mm and, with no time pressure, were required to verbally identify the letter. Identification accuracy was recorded and the method of Kitchen and Bailey (1981) used to calculate a log (min) threshold identification size. In this method the nominal threshold identification size is the smallest log (min) size at which 60% or more letters were read correctly, and a final threshold identification size is determined by adding 0.01 for each letter not read correctly at that size or the next largest size, and subtracting 0.01 for each letter read correctly at the next smallest size. This is a typical clinical approach to determining threshold identification size which has a reliability comparable with the use of a psychometric function (Hazel & Elliott, 2002).

The stimuli were presented in luminance blocks nested within colour blocks. Within each block, initially the smallest legible size was determined by presenting one randomly chosen letter of each size in descending size order until an error was made. All 10 letters of the smallest size correctly identified were then presented in random order. If fewer than four errors were made, all 10 letters of the next smallest size were presented, again in random order. This continued until four or more errors were made. Then all 10 letters of the next larger size than the size at which the first error was made were tested. If all letters were identified correctly the block was complete. If any error was made, all 10 letters of the next larger size were tested. Size continued to be increased until no errors were made, which completed the block. The order of presentation of the blocks was randomised. After all luminance blocks in a colour had been presented the preference stimulus was displayed and the participant was asked to indicate which line they preferred for ease and comfort of reading. An experimental session took approximately 45 minutes to complete, including one practice block at the beginning of the session.

In the low ambient lighting condition, the participants were alternately allocated to one of the two screen-background luminance levels based on order of testing and were given a 20-minute adaptation period. In the high ambient lighting condition, participants completed all luminance and colour conditions.

3. Results

The two ambient lighting conditions were analysed separately, and the log (min) threshold identification size was averaged across participants for each colour, character luminance and screen-background luminance condition. The effects of character luminance and screen background luminance on threshold identification size were initially analysed for each colour, and then the relative threshold size for each colour was compared. A significance level of $p = 0.05$ was used throughout with Bonferroni adjustments applied for multiple comparisons and Greenhouse-Geisser corrections were used where the assumption of sphericity was not met.

3.1 High Ambient Lighting

The mean threshold identification size for each character luminance and colour combination tested in the high ambient light condition is shown in the upper part of Table 2, and a plot of threshold identification size against character luminance for each colour is shown in Figure 3. An inspection of Figure 3 reveals that the minimum legible letter height initially reduced as character luminance increased but reached an asymptote, after which further increases in luminance failed to yield further improvements in minimum legible letter height. This pattern was evident for all colours except for primary blue, which failed to reach a threshold identification size asymptote.

Table 2: Mean log (min) threshold identification size and self-reported preferred character luminance for white, green, red and blue stimuli under each ambient lighting and screen-background luminance condition. Standard deviations are in parentheses.

High Ambient Light (260 lux)

Screen - Background Luminance 1.5 cd/m2

Color	Log (min) Visual Acuity – Character Luminance (cd/m2) 15.5	25.5	60.5	150.5	280.5	Mean Preferred Luminance for 0 Log (min) letters (cd/m2)
White	-0.05 (0.04)	-0.07 (0.05)	-0.09 (0.03)	-0.09 (0.02)	-0.09 (0.03)	132.5 (69.3)
Green	-0.06 (0.04)	-0.08 (0.05)	-0.09 (0.03)	-0.09 (0.04)	-	62.8 (53.6)
Red	-0.07 (0.04)	-0.09 (0.03)	-0.09 (0.04)	-	-	34.5 (17.4)
Blue	-0.01 (0.06)	-0.03 (0.05)	-	-	-	24.0 (3.1)

Low Ambient Light (1.5 lux)

Screen - Background Luminance .2 cd/m2

Color	Log (min) Visual Acuity – Character Luminance (cd/m2) 3.0	6.0	15.0	30.0	60.0	Mean Preferred Luminance for 0 Log (min) letters (cd/m2)
White	0.06 (0.08)	0.00 (0.08)	-0.04 (0.05)	-0.06 (0.05)	-0.05 (0.05)	36.0 (12.6)
Green	0.03 (0.07)	-0.01 (0.06)	-0.05 (0.06)	-0.04 (0.06)	-	17.1 (7.4)
Red	0.00 (0.09)	-0.03 (0.08)	-0.04 (0.08)	-	-	9.6 (4.6)
Blue	0.11 (0.08)	0.05 (0.07)	-	-	-	6.0 (0.0)
Screen - Background Luminance 1 cd/m2						
White	0.13 (0.05)	-0.01 (0.05)	-0.05 (0.03)	-0.06 (0.04)	-0.07 (0.03)	30.0 (12.2)
Green	0.08 (0.10)	-0.02 (0.06)	-0.06 (0.04)	-0.06 (0.04)	-	20.1 (8.9)
Red	0.02 (0.05)	-0.03 (0.05)	-0.07 (0.02)	-	-	10.5 (4.7)
Blue	0.22 (0.08)	0.08 (0.05)	-	-	-	6.0 (0.0)

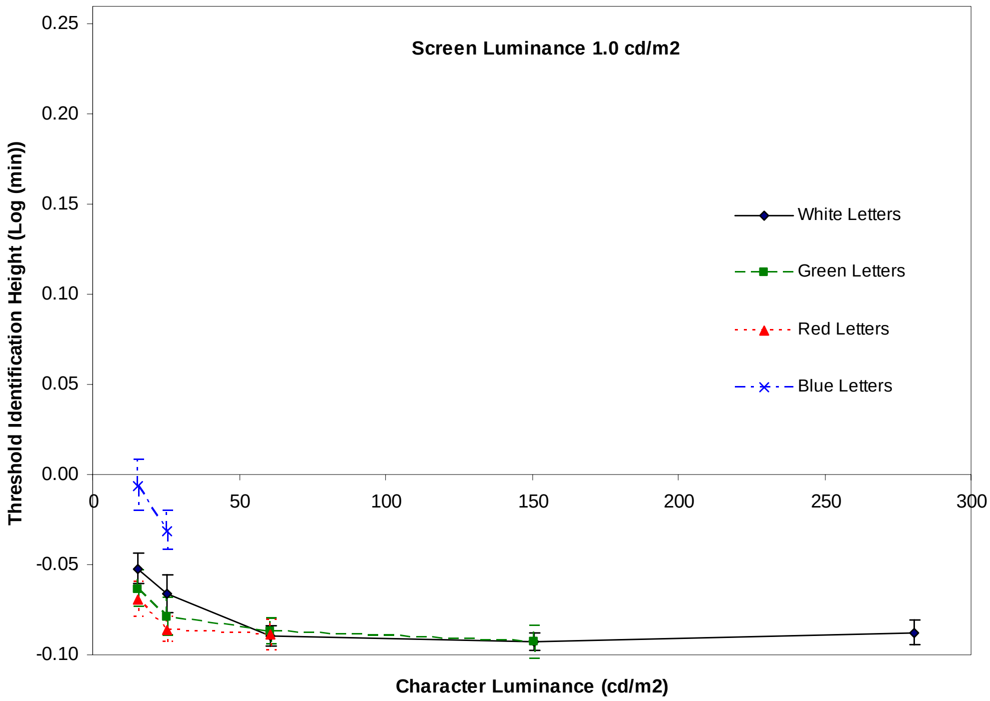

Figure 3: Mean threshold identification height at each character luminance for white, green, red and blue characters displayed over a screen-background luminance of 1 cd/m² with ambient lighting of 260 lux. Error bars represent ±1 standard error

3.1.1 The effect of character luminance on threshold identification size

Repeated-measures analyses of variance (ANOVAs) were performed to investigate the effect of character luminance on threshold identification size for all colours. Character luminance had a significant effect on the threshold identification size for all colours: $F(4,76) = 15.4$, $p < 0.001$ for white characters, $F(3,57) = 13.8$, $p < 0.001$ for green characters, $F(2,38) = 8.4$, $p = 0.001$ for red characters and $F(1,19) = 19.3$, $p < 0.001$ for blue characters. Repeated-measures paired contrasts revealed that, for white characters, threshold identification size decreased with increasing character luminance until a character luminance of 60 cd / m^2, after which no further significant reduction in the threshold identification size was found. The threshold identification size for green and red characters reduced as the character luminance increased from 15 cd / m^2 to 25 cd / m^2, but no significant improvement was seen as the character luminance increased from 25 cd / m^2 to 60 cd / m^2.

3.1.2 Self report preferred luminance levels

In addition to collecting acuity measures, data on self-reported preferred luminance levels for ease and comfort of reading were also collected. The mean preferred luminance for each colour is shown in Table 2. For blue letters, all but two participants preferred the highest achievable character luminance level (25 cd / m^2), which suggests a ceiling effect caused by an inability of the LCD to generate higher luminance levels for primary blue.

3.1.3 The effect of colour on threshold identification size

In addition to identifying the luminance level that produced the minimum threshold identification size for each character colour, the study aimed to identify whether the primary colours differed in legibility when equated for photopic luminance. The previous results suggest that the minimum threshold identification size may not be reached until character luminance reached 60 cd / m^2, but the maximum luminance at which all colours could be compared was 25 cd / m^2. Thus, a repeated-measures ANOVA was performed to determine the effect of colour on threshold identification size at a character luminance of 25 cd / m^2 to compare all the colours, and at a character luminance of 60 cd / m^2 to compare white, red and green at the minimum threshold identification size. For a character luminance of 25 cd / m^2, there was a significant effect of colour on acuity, $F(3,57) = 21.9$, $p < 0.001$, with pairwise comparisons indicating that the threshold identification size was significantly higher for blue than the other colours, which did not differ from each other. For a character luminance of 60 cd / m^2, there was no significant difference in threshold identification size for white, green or red, $F(2,38) = 0.00$, $p = .856$.

3.2 Low Ambient Lighting

The mean threshold identification size scores for each character luminance, character colour and screen-background luminance condition are shown in the lower portion of Table 2 and plotted in Figure 4. A plot of threshold identification size against character luminance for white letters in each screen-background luminance is shown in Figure 5.

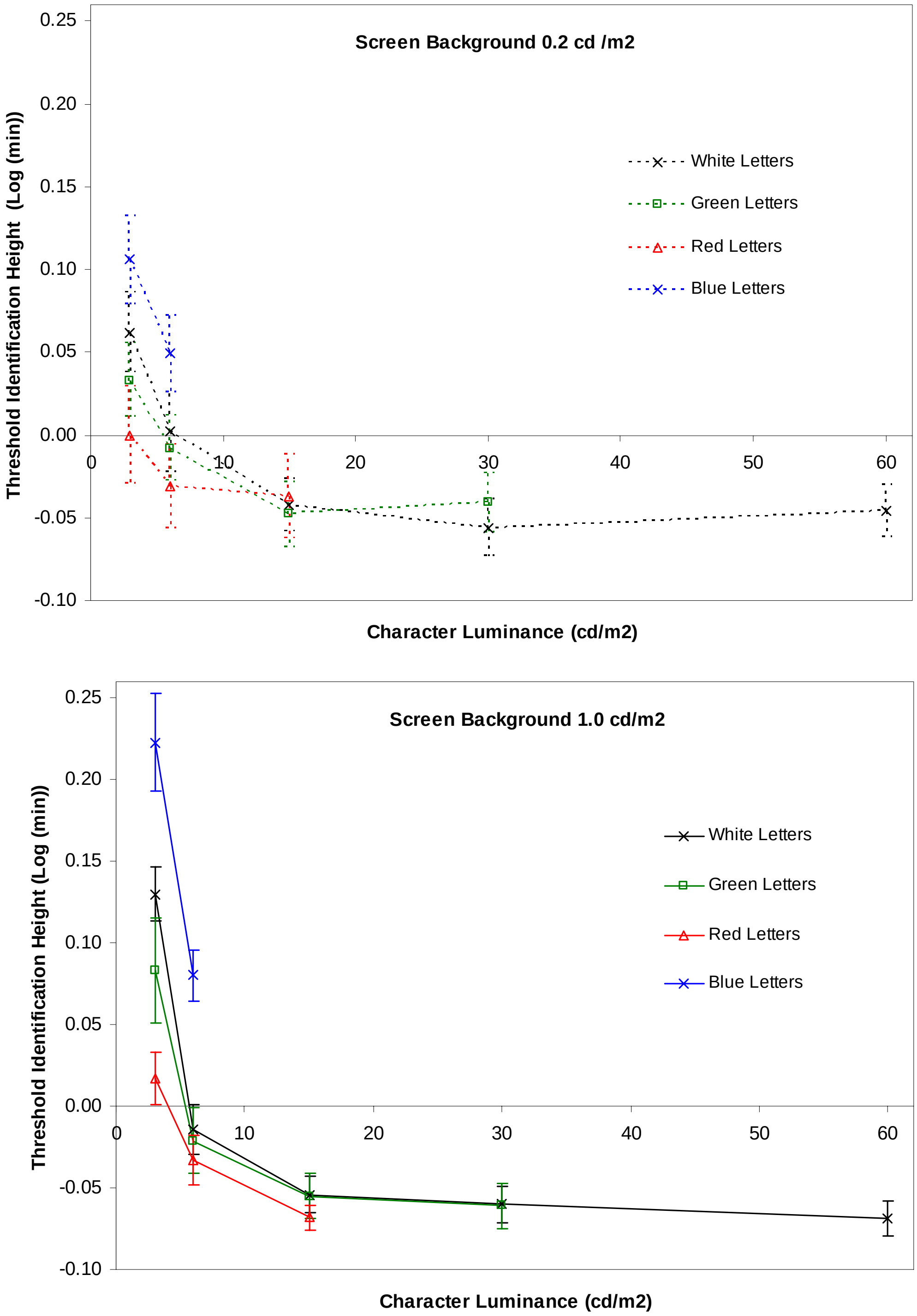

Figure 4: Mean threshold identification height at each character luminance for all character colours at screen background luminance levels of 0.2 cd/m² (upper plot) and 1.0 cd/m² (lower plot). Ambient lighting was 1.5 lux. Error bars represent ±1 standard error.

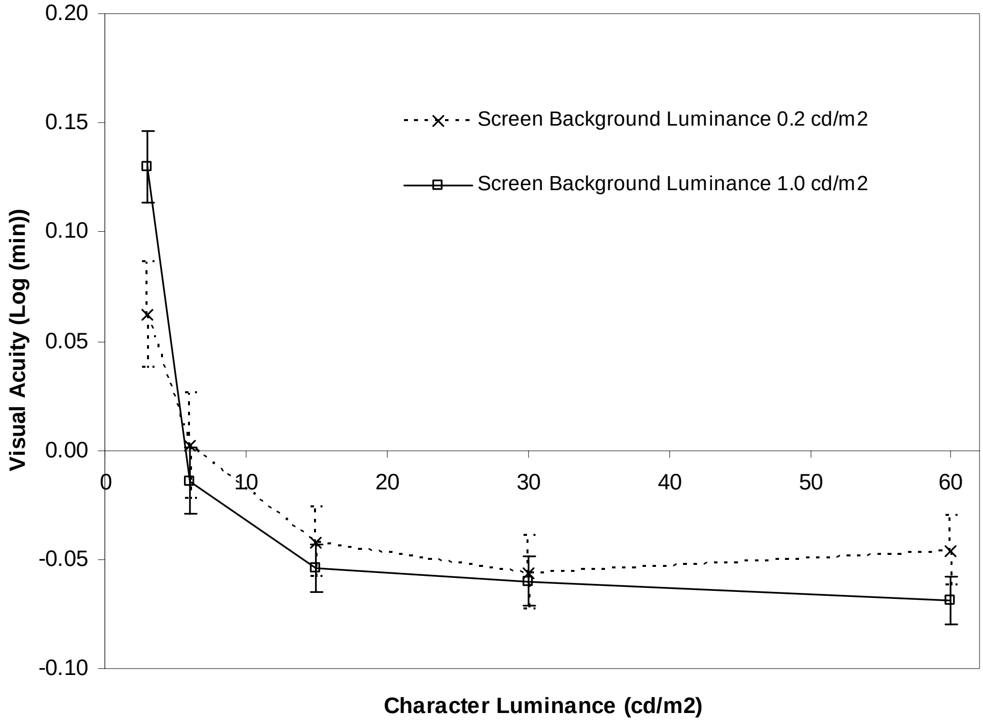

Figure 5: Mean threshold identification height at each character luminance for white letters at screen background luminance levels of 0.2 cd/m2 and 1.0 cd/m2 with ambient lighting of 1.5 lux. Error bars represent ±1 standard error.

3.2.1 The effect of character luminance and screen background luminance on threshold identification size

A mixed ANOVA with screen-background luminance as a between-subjects factor and character luminance as a within-subjects factor was performed for each character colour. Character luminance had a significant effect on the threshold identification size for all the colours: $F(4,72) = 132.9$, $p < 0.001$ white characters, $F(3,54) = 54.5$, $p < 0.001$ for green characters, $F(2,36) = 38.7$, $p < 0.001$ for red characters and $F(1,15) = 77.8$, $p < 0.001$ for blue characters. For white, green and red characters, the threshold identification size reduced as character luminance increased to 15 cd / m^2, but showed no statistically significant changes with further increases in luminance. Threshold identification size for the blue letters decreased significantly when character luminance increased from 3 cd / m^2 to 6 cd / m^2.

No significant main effect of screen-background luminance on the threshold identification size was observed for any colour: $F(1,18) = 0.02$, $p = 0.905$ for white characters, $F(1,18) = 0.01$, $p = 0.926$ for green characters, $F(1,18) = 0.03$, $p = 0.855$ for red characters and $F(1,15) = 4.0$, $p = 0.064$ for blue characters. However, there was a significant character luminance by screen-background luminance interaction for all the colours: $F(4,72) = 10.7$, $p < 0.001$ for white characters, $F(3,54) = 5.3$, $p = 0.019$ for green characters, $F(2,36) = 5.9$, $p = 0.006$ for red characters and $F(1,15) = 16.2$, $p = 0.001$ for blue characters. For white, green and blue letters, the interaction was significant as the character luminance changed from 3 cd / m^2 to 6 cd / m^2,

$F(1,18) = 16.4$, $p = 0.001$, $F(1,18) = 8.5$, $p = 0.009$ and $F(1,15) = 16.2$, $p = 0.001$ respectively. For red characters, a significant interaction occurred as the character luminance changed from 6 cd / m^2 to 15 cd / m^2, $F(1,18) = 8.5$, $p = 0.009$. For white characters, a significant interaction also occurred as luminance changed from 30 cd / m^2 to 60 cd / m^2, $F(1,18) = 5.3$, $p = 0.033$.

3.2.2 Self report preferred character luminance levels

The previous analysis identified the minimum luminance levels necessary to achieve the minimum threshold identification size. Data on self-reported preferred luminance levels were also collected for each condition. The mean preferred luminance level for ease and comfort of reading for each colour and background luminance level is shown in the lower portion of Table 2. For blue characters, all the participants preferred the highest level of luminance for blue, which suggests a ceiling effect caused by an inability of the LCD to generate primary blue at the higher luminance levels.

3.2.3 The effect of colour on threshold identification size

The previous results indicate that the minimum threshold identification size was reached for a character luminance of 15 cd / m^2, but the maximum luminance at which all colours could be compared was 6 cd / m^2. A repeated-measures ANOVA was performed to determine the effect of colour on the threshold identification size for a character luminance of 6 cd / m^2 in order to compare all colours, and for a character luminance of 15 cd / m^2 to compare white, red and green at the minimum threshold identification size. For a character luminance of 6 cd / m^2, there was a significant effect of colour on acuity, $F(3,51) = 28.5$, $p < 0.001$, with pairwise comparisons indicating that threshold identification size was significantly higher for blue than the other colours, which did not differ from each other. For a character luminance of 15 cd / m^2 there was no significant difference in the threshold identification size for white, green or red, $F(2,36) = 0.21$, $p = .811$.

4. Discussion

The current study aimed to identify the character luminance and luminance contrast levels that minimised the threshold identification size and optimised the self-reported comfort preference for white, primary red, primary green and primary blue letters when displayed on a modern, high resolution LCD with a dark background under high and low ambient lighting conditions. As characters become larger than the threshold identification size the required character luminance and luminance contrast should reduce, thus the current results should provide luminance and luminance contrast levels that are suitable for all letter sizes.

Under high ambient lighting, it appears that for a screen-background luminance of 1 cd / m^2 the minimum character luminance should be between 25 cd / m^2 and 60 cd / m^2, depending on the character colour. The threshold identification size for white characters began to increase rapidly if the character luminance was below 60 cd / m^2, and the threshold identification size for red and green characters began to increase if the character luminance was below 25 cd / m^2. Thus, 60 cd / m^2 can be seen as the minimum character luminance necessary to minimise the threshold identification size of all the colours tested. It may be possible to reduce this character luminance when displaying larger characters, but the mean self-reported preferred character luminance level was 132.5 cd / m^2 for the white characters, 62.8 cd / m^2 for the green characters and 34.5 cd / m^2 for the red characters. Given that the self report values were obtained when viewing a large number of characters of a size larger than the minimum threshold identification size, this suggests that, with the possible exception of red characters, a character luminance of 60 cd / m^2 will not be perceived as being too bright. Under low ambient lighting, the minimum character luminance for a display with a dark background should be approximately 15 cd / m^2. Again it may be possible to reduce this character luminance level when larger characters are displayed, but as self-reported optimum viewing comfort was obtained at luminance levels of approximately 33 cd / m^2 for white characters, 18 cd / m^2 for green characters and 10 cd / m^2 for red characters, such a reduction would not appear to be desirable. Given this range of preference levels, a character luminance of 20 cd / m^2 may be a reasonable compromise for the range of colours typically used in military displays.

The results also indicated that, under low ambient lighting conditions, a minimum luminance contrast of between 6:1 and 15:1 should be maintained, as evidenced by the effect of the different screen-background luminance levels on the threshold identification size at low character luminance levels. The threshold identification size was generally slightly smaller for a screen-background luminance of 1.0 cd / m^2 than for a screen background luminance of 0.2 cd / m^2, but this relationship was reversed when white, green and blue character luminance decreased below 6 cd / m^2 and when red character luminance decreased below 15 cd / m^2. At contrast levels below 6:1 for white and green characters and below 15:1 for red characters, the threshold identification size increased more rapidly as character luminance was reduced. The interaction of the screen background luminance and character luminance observed when white character luminance increased from 30 cd / m^2 to 60 cd / m^2 suggests that letter identification performance begins to be impaired if the luminance contrast is as high as 300:1.

Previous studies have found that a luminance contrast of between 2:1 and 4:1 is sufficient to optimise reading and visual search performance for character heights greater than 15 min (Legge et al., 1987; Nasanen et al., 2001; Ojanpaa & Nasanen, 2003; Roufs & Boschman, 1997). The current finding is that a minimum contrast of between 6:1 and 15:1 is required for the minimum threshold identification character size of 4.5 min. The higher contrast requirements of the current study are consistent with the expectation that the threshold contrast will reduce as the character size increases, and the current result can be considered the contrast level necessary to optimise legibility at all character heights. It could perhaps be argued that a contrast of 15:1 may be too high for larger character heights, as some studies have found decreased identification performance when the contrast ratio for negative polarity displays exceed approximately 10:1 (Roufs & Boschman, 1997; Zhu & Wu, 1990). However, the finding that identification performance decreases at high contrast levels is not consistently obtained and, in these studies, the screen-background luminance was comparatively high (between 20 cd / m^2 and 40 cd / m^2). It may be that the high screen-background luminance levels contributed to the reduction in performance at high contrast levels.

In terms of the effect of colour, the current results show that there was no significant difference in the threshold identification size between white, primary red and primary green characters for almost all character luminance conditions. Thus when these colours are presented on an LCD at the same photopic luminance, they appear to be equally legible. However, primary blue characters exhibited two problems: they could not be generated at luminance levels sufficient to reach asymptote threshold identification size and they had significantly worse legibility than all the other colours at each luminance level tested. A blue-on-black colour combination produces poor legibility due to the characteristics of the human visual system such as the low density of cones sensitive to blue light in the fovea (Castano & Sperling, 1982; Williams, MacLeod, & Hayhoe, 1981). It appears that, despite the possible changes to the spectral characteristics of primary blue in modern LCDs to alleviate this problem (Arend et al., 2005), it remains a poor choice of colour on a dark background. One solution, which appears to have been adopted in MIL-STD-2525B (DoD, 1999), is to shift the chromaticity of blue characters by introducing low levels of primary green to generate a colour that is closer to 'cyan'.

At the suggested character luminance and contrast levels, the minimum legible letter height was approximately 4.4 min under dark ambient lighting and approximately 4.1 min under bright ambient lighting. A general heuristic for determining the minimum text size for optimal readability is that it should be three times the size of the acuity limit (Bullimore, Howarth, & Fulton, 1995). However, a more accurate multiple may be 2.5 times the acuity level (Chung, Mansfield, & Legge, 1998). Using a multiple of 2.5, the measured minimum letter heights under the various viewing conditions suggests that a letter height of between 10 min and 11 min will be required to achieve maximum reading speed. A follow-up study aimed to directly measure the text sizes necessary to enable fast and accurate identification of text and symbols (Fletcher et al., 2009).

The results of the current study suggest that for LCDs using dark screen backgrounds, a character luminance of approximately 60 cd / m^2 is appropriate under high ambient lighting levels and a character luminance of approximately 20 cd / m^2 is appropriate under low ambient lighting conditions. The high ambient lighting level of 260 lux used in the current study was specifically chosen to match the brightly illuminated naval operations room conditions, but is also at the low end of recommendations for office-based computer work, which range between 200 lux and 750 lux (Boyce, 2003). It may be that different ambient light levels might cause changes to the adaptation level in the eye and lead to a different optimum character luminance. However, Lin and Huang (2006) found that changing ambient light from 200 lux to 800 lux had no influence on the luminance contrast setting that optimised the character identification performance on a thin film transistor LCD. Thus, the optimum character luminance found in the current study is likely to be suitable for the typical range of office illumination conditions. The specific ambient light level of 1.5 lux was chosen to match that of darkened military operations rooms, but the current results could also have application to displays with dark backgrounds used at night, such as car dashboard displays and automated teller machines.

5. Conclusions

The following conclusions can be drawn from the study concerning negative polarity displays (bright characters over a dark background) on an LCD:

- When viewed under the lighting conditions experienced in dark naval ops rooms the characters should have a luminance of approximately 20 cd / m^2 to balance legibility and preferred ease and comfort of reading over all colours tested.
- When viewed under the lighting conditions experienced in bright naval ops rooms (which are similar to normal office lighting levels) the character luminance should be approximately 60 cd / m^2. This character luminance level should balance legibility and preferred ease and comfort of reading over all colours tested.
- The contrast ratio between the character luminance and the screen background should be at least 6:1.
- There is no difference in the threshold identification size between white, primary red and primary green characters displayed at equivalent photopic luminance. However, primary blue characters had lower acuity than the other colours and its use is not recommended. A mixture of primary blue and primary green may produce a colour that is perceived as blue and can achieve acceptable acuity levels.

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19. ABSTRACT

This study aimed to identify the luminance and contrast levels necessary to minimise the threshold identification size of bright letters displayed over a dark background on an LCD under low (1.5 lux) and high (260 lux) lighting conditions. White, pure red, pure green and pure blue upper-case Bailey Lovie letters with a contrast between 3:1 and 300:1 were displayed on an LCD to 20 participants. The threshold identification size was equivalent for all colours except for blue, which had larger threshold identification size than white, red and green at all character luminance levels tested. The threshold identification size initially decreased as character luminance increased, but asymptoted to a minimum size after which further increases in character luminance yielded no additional significant reduction in the threshold identification size. The threshold identification size was relatively insensitive to contrast provided the contrast level was above 6:1. Self-report preferred character luminance levels were generally higher than the character luminance levels necessary to achieve minimum threshold identification size. It is recommended that character luminance should be approximately 20 cd/m2 under dark lighting conditions and approximately 60 cd/m2 under bright lighting conditions. These values translate to contrast levels of 20:1 and 60:1 under the suggested screen background luminance of 1.0 cd/m2.