Human contrast-detail performance with declining contrast

Alisa Walz-Flannigan

Mayo Clinic, Rochester, Minnesota 55905

Ben Babcock

American Registry of Radiologic Technologists, Minneapolis, Minnesota 55120

George C. Kagadis^{a)}

Department of Medical Physics, School of Medicine, University of Patras,
P.O. Box: 132 73, GR 265 04 Rion, Greece

Jihong Wang

University of Texas, MD Anderson Cancer Center, Houston, Texas 77030

Steve G Langer

Mayo Clinic, Rochester, Minnesota 55905

(Received 22 February 2012; revised 26 June 2012; accepted for publication 23 July 2012;
published 16 August 2012)

Purpose: How do display settings and ambient lighting affect contrast detection thresholds for human observers? Can recalibrating a display for high ambient lighting improve object detection?

Methods: Contrast/detail (CD) threshold detection performance was measured for observers using four color displays with varying overall contrast (e.g., differing maximum luminance and ambient lighting conditions). Detailed mapping of contrast detection performance (for fixed object size) was tracked as a function of: display maximum luminance, ambient lighting changes (with and without recalibrating for the higher ambience), and the performance of radiologists vs. nonradiologists.

Results: The initial phase was analyzed with a hierarchical linear model of observer performance using: background gray level, maximum display luminance, and radiologist vs. nonradiologist. The only statistically significant finding was a maximum luminance of 100 cd/m² display performing worse than a baseline peak of 400 cd/m². The second phase examined ambient lighting effects on detection thresholds. Background gray level and maximum display luminance were examined coupled with ambient lighting for: baseline at 30, 435 uncorrected, and 435 lx with display recalibration for the ambient conditions. Results showed ambient correction improved sensitivity for small background digital driving level, but not at higher luminance backgrounds.

Conclusions: For CD study, nonradiologist observers can be used without loss of applicability. Contrast detection thresholds improved significantly between displays with peak luminance from 100 cd/m² to 200 cd/m², but improvement beyond that was not statistically significant for contrast detection thresholds in a reading room environment. Applying a calibration correction at high ambience (435 lx) improved detection tasks primarily in the darker background regions. © 2012 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4742851>]

Key words: ambient lighting, contrast/detail performance, observer studies, display, GSDF, luminance, human visual system

I. INTRODUCTION

The diagnostic medical physics profession is charged with informing the practice of radiology in regards to many details of legal, ethical, and standards of practice in medical imaging. This is not merely confined to the dose management of ionizing radiation imaging systems, but preservation of image quality through all links in the interpretation process—including the display. In some cases there is the force of law behind display standards. Mammography facilities must be certified under the mammographic quality standards act (MQSA) in order to legally perform screening mammograms in the United States, and the mammographic display settings and quality control program are part of the certification checklist.^{1–3} The majority of other imaging areas are affected by accreditation guidelines that can affect reimbursement,⁴

and there are varying degrees of prescription for display settings.

The Academic College of Radiology (ACR) Technical Standard for the Electronic Practice of Medical Imaging⁵ makes several recommendations regarding display criteria including: maximum and minimum luminance, minimum luminance ratio, and calibration to the Digital Image Communications in Medicine Gray Scale Display Function (DICOM GSDF).^{6,7} These recommendations have evolved over time. For example, the 2004 ACR MRI Quality Control Handbook⁸ which is still relevant for MRI accreditation today says the maximum display luminance should be above 90 cd/m². The 2007 version of the ACR Technical Standard⁹ suggested a maximum luminance for diagnostic displays to be above 171 cd/m², in the 2012 revision the recommended maximum luminance is above 350 cd/m².⁵

TABLE I. Summary of previously published work describing the effect of luminance settings on detection-task performance.

Reference	LCD/CRT	Calibration	Min lum (cd/m ²)	Max lum (cd/m ²)	Ambient (lx)	Subject images	Findings/recommendation
Herron <i>et al.</i> (Ref. 23)	Film on computer controlled light-box	None. Film used	Unknown minimum	85, 260, 770	Unknown ambient	Chest radiographs	ROC study with 6 readers and 569 images. Pneumothorax and interstitial lung disease showed significant difference between all luminance settings (770 cd/m ² was the best). Rib fracture AUC showed difference between luminance of 85 cd/m ² and that of either 260 or 770 cd/m ² .
Ikeda <i>et al.</i> (Ref. 24)	CRT	Non-DICOM; characterized, not calibrated	7.0–11.4	157.4–369.0	200	Chest radiographs	13 radiologists examined 11 chest images with simulated nodules under 11 different luminance conditions. Nodule detection degraded below 224 cd/m ² max luminance compared to higher luminance (up to 369 cd/m ²).
Goo <i>et al.</i> (Ref. 25)	CRT	None. Displays adjusted to make 5% and 95% on SMPTE visible. Users could adjust window width and level.	Not provided	86, 171, 342	0, 50, 460	Chest radiographs	No difference between luminance or ambient settings on the ability to detect nodules, pneumothorax or interstitial disease. Impact on fatigue was measured.
Hidano <i>et al.</i> (Ref. 26)	CRT	Non-DICOM; characterized, not calibrated	7.0–11.4	157.4–369.0	200	Chest radiographs	Same conditions as Ikeda <i>et al.</i> (Ref. 24) but with randomized ordering and different analysis technique. Nodule detection degraded below 246 cd/m ² max luminance compared to higher luminance (up to 369 cd/m ²).

There is a cost associated with maintaining displays at a higher luminance. This is because the cold-cathode fluorescent lamps used for backlights in typical liquid crystal displays (LCDs) will dim over time. Maintaining a higher maximum luminance involves replacing failed displays, or replacing their backlights more frequently when they can no longer achieve the desired maximum output. Because there is variable interpretation as to the impact of the ACR technical standard on accreditation (the ACR MRI QC Handbook would be the authoritative guide for MRI),⁸ and concern over the cost of maintaining a higher luminance, we are challenged by our practice to justify the extra expense with maintaining a higher luminance output.

A literature search has not entirely succeeded in answering the fundamental question, “How much maximum luminance (or luminance ratio) is enough in the real world of a radiology practice?” While many standards and articles recommend particular luminance or luminance ratio settings, it is difficult to find research studies which actually address these variables explicitly. Several existing studies are summarized in Table I, none of which use DICOM calibration.

Many more studies have looked in to the effect of ambient light for fixed calibration conditions.^{10–15} However, in addition to understanding the benefit (or penalty) of particular ambient lighting, we want also to know how to handle typical lighting for a variety of situations (reading room range and clinical area range). There are different recommendations for handling the effects of higher ambient lighting. The DICOM GSDF,⁷ which is the calibration standard advocated by the ACR and widely used in radiology, incorporates measurement of ambient light reflection in calibration and conformance testing. Despite this, most displays for use in radiology come with vendor-provided calibration programs that use a contact photometer and do not measure the impact of ambient light on DICOM conformance. If a display vendor provides an ambient light compensation feature it is often accomplished by simply raising the minimum luminance value (instead of shifting each DDL in response). This is the method of ambient light compensation that is recommended in the ACR Technical Standard^{5,9} and the AAPM TG 18 Report.¹⁶ However, there is little information in the literature to reinforce the particular advocated luminance settings and the overall effect can be to significantly depress luminance ratios.

The goal of our study was to examine the effect of different display settings in two different ambient light viewing conditions corresponding to reading room lighting (30 lx) and clinical or procedural room lighting (435 lx). The questions posed are the ones we wanted addressed for our own practice. Three primary questions were investigated:

1. What is the optimal maximum luminance setting for either low or high ambient viewing conditions with a fixed minimum luminance (black level) of 0.5 cd/m²? This minimum luminance value meets the recommendations in the AAPM TG 18 report and the 2007 revision of the ACR Technical Standard for typical reading room ambient lighting.^{9,16}
2. Using the same display calibration setting as for question 1 (with no ambient light compensation), what is the effect on contrast discrimination thresholds with higher ambient lighting conditions?
3. What is the effect on the contrast discrimination threshold if the display is recalibrated to compensate for higher ambient light (in concordance with the DICOM GSDF)?

All the displays used in our radiology practice are calibrated to the DICOM GSDF (without ambient light compensation). The purpose of having a DICOM GSDF calibrated display includes a desire to have a consistent presentation of images between displays and to provide perceptual uniformity across the gray scale for any given display. Perceptual uniformity across the gray scale means that a change of one Digital Driving Level (DDL) at any luminance will have the same perceived magnitude of change. This assumption of perceptual uniformity across the gray scale with DICOM GSDF calibration is truly only appropriate for conditions of variable adaptation.¹⁴ Variable adaptation is the condition on which the Barten model is conceived, where the average luminance of a small test pattern is the same as the background luminance. Actual radiologic images may contain a variety of bright and dark regions, and the object of interest may not correspond to the adapted luminance of the eye; this viewing condition is described as fixed adaptation. The experimental model described in our methods is close to the variable adaptation model, though our study does use spherical nodules as opposed to the sinusoidal gratings used for the Barten-model studies.

The Barten model, upon which the DICOM GSDF is based, reflects the nonlinear nature of the human visual system (HVS) and provides a function for how much change in contrast would be noticeable at a specific background luminance. For each background luminance to which the eye adapts, this model describes the smallest amount of contrast that is visible, known as the just noticeable difference (JND). The size of a JND (in terms of luminance change) increases with luminance, meaning that larger luminance changes are required for the same visibility as the background luminance increases.

This JND concept can be helpful in further describing display calibration. The amount of contrast change between of any two DDLs can be expressed in terms of JND. For percep-

tual uniformity across the gray scale, the calibration aim is to make the number of JNDs between each DDL the same. A larger overall display luminance ratio means that there can be more JND per DDL. However, because of the nature of the human visual system there are diminishing returns with increasing luminance ratio in terms of increasing JND/DDL. Because the JND model is based on a variable-adaptation in reality for more realistic viewing conditions (with fixed adaptation) there are diminishing returns with increasing JND/DDL as our eyes cannot fully appreciate an ever-widening luminance range.¹⁷

But what happens when we add in ambient light? Ambient light reflected from a display creates additive luminance to whatever is displayed. When this light is added to a display that is calibrated to the DICOM GSDF (without ambient correction) each luminance step has been shifted and thus may not have the same number of JND per DDL. Because of the nonlinearity of the HVS, the number of JND/DDL will be most decreased for low DDL and barely changed for high DDL, the extent of this change depends on the magnitude of the ambient light. Thus, with ambient light a DICOM GSDF calibrated display will no longer be perceptually uniform and there will be loss of contrast especially at low DDL.

To mitigate the loss of contrast for low DDL that occurs with the addition of ambient light (and impact on GSDF calibration) the AAPM TG-18 report recommends using a black level of 1.5 times the ambient light reflection (in the 2012 version of the ACR Technical Standard this factor is 4). With a higher minimum luminance the impact of higher ambient (or variation in ambient light) has less effect on the JND/DDL and the deviation from perceptual uniformity is less. However, one could also address the presence of ambient light by measuring its contribution at each luminance step and accommodating this in the DICOM GSDF calibration. In this study, where we have a known ambient light, we have kept the same minimum luminance and accounted for the additional ambient light with setting the luminance value of each DDL. This allows us to maintain better perceptual uniformity and still take advantage of a larger luminance range of a display.

To examine the impact of different settings and viewing conditions we performed a contrast/detail (CD) study. To increase the sensitivity of discriminating user performance with different display conditions, and to have a closer resemblance to clinical findings, we have used a software program that uses a free search for a spherical nodule (a fuzzy-edged object). Use of the projected spherical nodule was shown to better discriminate between display settings than a solid disk and these objects may also more closely mimic radiological images.¹⁸ This software can be used to map out a contrast-detail response curve for an average observer.

II. MATERIALS AND METHODS

The study is broken down into the following parts:

Phase I

- (a) Assess if a significant performance difference exists on the CD task between radiologists and nonradiologists.

If not, this simplifies observer recruitment for subsequent work.

- (b) Measure observer CD detection thresholds with varied maximum luminance with a fixed minimum luminance for lower ambient light setting.

Phase II

- (a) Measure change in the contrast detection threshold change when the displays are viewed in different ambient lighting (30 lx or 435 lx).
- (b) In the high ambient setting, observe change in the contrast detection threshold if the display is recalibrated to account for the ambient lighting.

II.A. Data acquisition

Four LCDs were used for this study, all of which were Eizo RX320 3MP, 21.3", pixel size = 0.21075×0.21075 mm (Eizo, Ishikawa, Japan). For all portions of this study, the displays were calibrated using the Eizo RadiCS software and the Eizo provided contact photometer. The luminance of each display was checked daily. The room ambience was measured by a Fluke Model 7-621 photometer (Fluke Biomedical, Cleveland, OH).

Four displays were required to establish the four different calibration conditions considered in each phase of the study. Each display was viewed sequentially and test patterns were displayed only on the display being viewed to maintain the measured ambient lighting control. Ambient light was separately measured in front of each display. The selected maximum luminance level settings were 100 cd/m² (required by ACR MR QC guidelines), 200 cd/m² (from the ACR 2007 Electronic Practice Guidelines), 300 cd/m² and 400 cd/m² (two luminance levels considered for our PACS and clinical workstation displays). The calibrated minimum luminance was 0.5 cd/m². Other differences in calibration and viewing between the phases of the study are described in Secs. II.A.1 and II.A.2 and summarized in Table II. The cases shown are those used in the study: low ambient lighting (30 lx), higher ambient of 435 lx without ambient light compensation in the calibration (uncorrected), higher ambient of 435 lx with ambient light compensation in the calibration (corrected).

An automated software program was used to map out viewers' CD curves by displaying projections of simulated

spherical nodules of variable size, luminance, and background luminance.^{19,20} The simulated spherical nodules themselves are equivalent to two-dimensional x-ray projection images of spheres, defined by a maximal pixel value difference from background ($I_{\text{Max}} - I_{\text{background}}$), and a pixel diameter, R .¹⁸ The equation describing the luminance values of the projection (I) is

$$I(x, y) = \frac{I_{\text{Max}}}{R} \sqrt{R^2 - (x^2 + y^2)}. \quad (1)$$

Because this image is created with an 8-bit digital display, the luminance values for these objects are quantized. The actual luminance values of the object would be rounded to the nearest DDL from the value described by Eq. (1). For viewers, neither luminance nor spatial quantization was visibly apparent for any of the objects.

When the program is launched, a series of test images generated by the program are presented to the observer. In each of the test images, a single object is presented at a random location (within a central 500×500 pixel region) on the monitor on a uniform background. Observers interact with the computer by pointing and clicking on the target when he or she can see the simulated nodular target, and the program automatically records the contrast thresholds of the observers for various object sizes and background luminance levels. If the viewers were unable to locate the object and "gave up" after a period of time, they were asked to select the area outside the central ROI indicating to the software that they did not find it. No window/level adjustment was available thus the calibrated look-up-table (LUT) (the input pixel to luminance level conversion table) is not altered. The lowest visible object contrast (measured as the differences in DDL between the object and its uniform background) is automatically recorded by the program as the contrast threshold for that particular object size. This procedure is repeated for all preset background luminance levels (DDL) and object sizes thus the contrast-detail curves are obtained.

II.A.1. Phase I study details

This phase provided CD data at a lower ambient lighting level (equivalent to a reading room setting of 30 lx). All displays were calibrated to the DICOM GSDF with no ambient light compensation selected. Displays had a minimum luminance of 0.5 cd/m² and variable maximum luminance (Luminance_{MAX}). The observer's workstation consisted of the layout we use clinically, with four diagnostic displays (positions 1, 2, 3, and 4 from left to right) in portrait orientation angled with the observer at the "focus" and with a nominal eye to screen distance of 30 cm. A schematic of this is shown in Fig. 3. Each display was calibrated differently and left in their respective positions from left to right: position 1 = Luminance_{MAX} of 400 cd/m², position 2 = Luminance_{MAX} of 300 cd/m², position 3 = Luminance_{MAX} of 200 cd/m², position 4 = Luminance_{MAX} of 100 cd/m².

Each observer was tasked with finding a spherical nodule (of 8, 22, 36, 50 pixel diameter) at four different background

TABLE II. Summary of display settings and viewing conditions considered in the current study. The cases shown are for low ambient lighting (30 lx), higher ambient (435 lx) without ambient light compensation in the calibration (uncorrected), higher ambient (435 lx) with ambient light compensation in the calibration (corrected).

Viewing condition	L _{ambient} (cd/m ²)	L _{MIN} (cd/m ²)	L _{MAX} (cd/m ²)
Ambient (30 lx)	0.18	0.5	100, 200, 300, 400
Ambient (435 lx) uncorrected	2.6	0.5	100, 200, 300, 400
Ambient (435 lx) corrected	2.6	0.5	100, 200, 300, 400

TABLE III. Realized JND/DDL values for different display settings and viewing conditions. The high ambient (435 lx)-corrected case has been recalibrated for perceptual linearity as reflected by the equal max and min JND/DDL values. For the high ambient (435 lx), uncorrected case, the JNDs/DDL at low DDL are small (<1).

Viewing condition	JND/DDL (100 cd/m ²)	JND/DDL (200 cd/m ²)	JND/DDL (300 cd/m ²)	JND/DDL (400 cd/m ²)
Ambient (30 lx)	Average: 1.64	Average: 2.01	Average: 2.24	Average: 2.4
	Min: 1.4	Min: 1.71	Min: 1.91	Min: 2.04
	Max: 1.67	Max: 2.05	Max: 2.28	Max: 2.44
Ambient (435 lx) uncorrected	Average: 1.37	Average: 1.78	Average: 1.95	Average: 2.12
	Min: 0.55	Min: 0.65	Min: 0.72	Min: 0.78
	Max: 1.64	Max: 2.02	Max: 2.26	Max: 2.43
Ambient (435 lx) corrected	Average: 1.37	Average: 1.74	Average: 1.96	Average: 2.13
	Min: 1.37	Min: 1.74	Min: 1.96	Min: 2.13
	Max: 1.37	Max: 1.74	Max: 1.96	Max: 2.13

luminance values (50, 113, 176, 239 DDL) on each of the four displays.

For the CD task, a difference between radiologist and non-radiologists was not expected. However, this assumption was explicitly checked by using separate cohorts of radiologists and nonradiologists (a group of eight board certified radiologists and 12 technologists, programers, and medical physicists).

II.A.2. Phase II study details

For this phase the impact of ambient lighting and a calibration correction for ambient lighting was investigated.

Having shown equivalence between radiologist and non-radiologist observers, a primarily nonradiologist cohort (with participants from the original group, augmented with others) was used to address the additional questions outlined above. The study size was roughly maintained with a total of 18 observers (one of whom was a radiologist).

Because of the challenge of attaining uniformly illuminated displays, when higher-ambient conditions were present each display was brought to position 2 (see Fig. 1) for observation. In addition, participants were asked to remove white labcoats or name badges which might cause additional glare on the displays. Specific clothing was not mandated, though no participant in the high ambient study wore a white shirt.

FIG. 1. Schematic of study setup, showing relative positions of displays and observer.

In Phase II(a), no change was made to the display calibrations from Phase I. We simply wanted to observe the impact of higher ambient lighting if no correction was employed. In Phase II(b), an ambient light correction was programmed into the GSDF calibration. This ambient light correction strategy was very simple. The study used the same minimum and maximum luminance as for the previous phases, but the measured ambient light and the diffuse reflection coefficient of the displays was used to determine the ambient lighting contribution to each DDL. The luminance for each DDL was adjusted so that when the ambient contribution was included the contrast change between each DDL would have the same number of JNDs. This strategy attempts to maintain the perceptual uniformity of the GSDF with consideration for the ambient lighting. We used an Eizo contact photometer to calibrate displays with a custom LUT based on the strategy described. The impact of ambient lighting and calibration correction (or lack thereof) on JND/DDL is summarized in Table III.

For this phase the study data were collected for two spherical nodule sizes: 22 and 36 pixels in diameter; these nodule sizes showed discrimination in the detection threshold between displays in the earlier phase of the study, as described in Sec. III.A. The same four background luminance levels were used as in Phase I (50, 113, 176, 239).

II.A.3. Data analysis: Phase I

Because each display is calibrated to a different maximum, the same DDL on each display will correspond to a different luminance value. This means that the threshold DDL values will correspond to different luminance differences on different displays. Also because of the nonlinearity of the DICOM GSDF, the DDL threshold difference in terms of luminance will be different for different background DDL. Because image information maps to the same DDL on each display, detection requiring a greater threshold DDL may mean that an object is missed or harder to find than if the threshold was lower.

First, the one-dimensional conditional means (i.e., controlled for only one but not all factors) for the contrast detection threshold were modeled. These means are useful for

an overview of how the variables in the study are functioning. While these results are interesting, simply examining means aggregated across all other factors does not control for important facets of the experimental design. Interpretation based simply on means alone gives an incomplete picture of the data.

A more complete picture of the data is obtained using a hierarchical linear model (HLM, also known as a multilevel model or a random effects linear model) with random intercepts for people and fixed effect predictor coefficients. One can use the results of a HLM to examine how the different levels of a factor performed while statistically controlling for all other variables. This type of model accounts for each individual's repeated performances on the object identification task. It is important to use a statistical model that accounts for repeated measures, because treating all observations as experimentally independent will lead to inaccurate standard errors and, thus, inaccurate statistical conclusions.²¹ The authors were only interested in the quantities for the fixed-effect terms. The significance of all terms was evaluated using α of .001 in order to control for the family wise error associated with conducting a large number of hypothesis tests. The authors fit the HLM using maximum likelihood.

II.A.4. Data analysis: Phase II

The same data analysis techniques for Phase II were used as in Phase I.

III. RESULTS

III.A. Phase I study

The CD detection threshold data are shown in Fig. 2 for various display luminance settings. Observer results did not show significant variation in detection thresholds for various viewing conditions with targets larger than 22 pixels (i.e., the detection task was too simple to discriminate amongst the displays). In contrast the behavior for both the 22 and 8 pixel diameter targets showed similar average effects for CD detection threshold differences between displays. However, the contrast threshold for 8-pixel size is significantly larger than for 22-pixels and the viewer variability sufficient to suggest that for many viewers this task was too difficult (for all viewing conditions). Such results suggest that the 8-pixel size object would not be ideal for distinguishing differences between viewing conditions. Subsequent data analysis was simplified for focus on discrimination in contrast detection thresholds between lighting and display settings for the 22 pixel target data only.

Table IV contains the overall and one-dimensional conditional means for the identification threshold (smaller threshold indicates the object was easier to see). The reader should keep in mind that these conditional means only split the data based on the listed variable and not the other listed variables. The only variable that appears to affect the mean threshold DDL delta is display luminance (L_{MAX}). The difference in threshold DDL between a 100 cd/m^2 and 400 cd/m^2 L_{MAX} is nearly 1 DDL, though no difference is mea-

FIG. 2. Shows the mean contrast-detail detection threshold conditions for the average observer with a background DDL of 50 for varying object size and maximum calibrated luminance, ambient light = 30 lx.

sured between the other luminance settings. The difference between radiologists and nonradiologists while somewhat different appears to be insignificant.

The authors fit a variety of HLMs, but the model that fits the best while maintaining parsimony was the main effects model. No model provided a significantly better fit than the main effects model, which indicates there were few significant interaction effects for these conditions. Table V contains model fit information comparing the unconditional (null) model with the fixed effects model. The unconditional model accounts only for the means of the individual participants in the study. The unconditional model, therefore, has no actual predictor variables. Comparing a HLM with predictors to an unconditional model is important to ensure that the HLM has no prediction power at all. The fixed effects model fits significantly better than the unconditional model, although in terms of R squared the fit was low-to-moderate; the pseudo- R squared for the fixed model was 0.12 ([1.49–1.31]/1.49).

TABLE IV. Phase I overall and one-dimensional conditional descriptive statistics for identification threshold.

		Mean	SD
Overall threshold DDL		4.9	1.6
Background DDL	50	5.0	1.7
	113	4.7	1.5
	176	5.1	1.6
	239	5.1	1.6
	400	4.7	1.6
L_{MAX} (cd/m^2)	300	4.7	1.4
	200	4.7	1.4
	100	5.6	1.8
	No	4.9	1.6
Radiologist	No	4.9	1.6
	Yes	5.1	1.7

TABLE V. Phase I fit comparison of unconditional (null) and fixed effects model with likelihood ratio test for fit improvement.

Unconditional (null) model		Fixed effects model	
Fit statistics		Fit statistics	
AIC	Log likelihood	AIC	Log likelihood
1092.5	−543.2	1064.0	−523.5
Random effects		Random effects	
Term	Variance	Term	Variance
Intercept	1.09	Intercept	1.10
Residual	1.49	Residual	1.31
Likelihood ratio fit test			
Model	df	Log likelihood	<i>p</i>
Unconditional	3	−543.2	
Fixed effects	10	−523.5	39.4
			<0.001

Table VI contains the fixed effect model results for an ambient lighting of 30 lx. In this particular presentation, the base (intercept) condition corresponds to an individual who is viewing the screen with a background luminance of 50 DDL, a display Luminance_{MAX} of 400 cd/m², and is not a radiologist. The dependent variable in this model was the threshold required for an individual to successfully identify the 22 pixel object on screen. The coefficients displayed represent the amount of change from the baseline condition when this condition was manipulated, assuming that all other factors were constant. Higher thresholds indicate that participants had a more difficult time with identification. Positive coefficients in the statistical model, therefore, indicate worse performance than the base condition, while a negative coefficient indicates better performance.

There are several interesting results from this analysis. The first result is the performance of radiologists *vs.* nonradiologists. The nonsignificant coefficient for radiologist indicates that there was no significant difference between the radiologists and nonradiologists. The coefficient for the radiologist variable was positive, indicating that nonradiologists performed slightly *better* than radiologists, though the difference

TABLE VI. Phase I HLM fixed effects results. Intercept (baseline) condition: 50 DDL, a display Luminance_{MAX} of 400 cd/m², nodule size of 22 pixels, and viewer is not a radiologist.

HLM fixed effects	Coefficient	SE	df	<i>t</i>	<i>p</i>
Intercept	4.63	0.34	294	13.48	<0.001
Background DDL 113	−0.29	0.18	294	−1.57	0.117
Background DDL 176	0.09	0.18	294	0.48	0.633
Background DDL 239	0.10	0.18	294	0.55	0.585
Luminance _{MAX} 300	0.06	0.18	294	0.34	0.733
Luminance _{MAX} 200	0.06	0.18	294	0.34	0.733
Luminance _{MAX} 100	0.93	0.18	294	5.05	<0.001
Physician	0.19	0.52	18	0.37	0.714

Note: Coefficient = HLM fixed-effects coefficient (units are DDL), or change from intercept condition; SE = standard error; df = degrees of freedom; *t* = *t* coefficient testing the null hypothesis that the coefficient is 0, *p* = *p*-value corresponding to the *t* coefficient.

was indeed nonsignificant. There were also no statistically significant interaction terms involving the radiologist variable in any of the more complicated models that the authors explored, indicating that radiologists and nonradiologists did not perform differentially conditioning on other factors.

The coefficients for Luminance_{MAX} indicated the lowest Luminance_{MAX} (100 cd/m²) led to worse performance on the contrast detection task. The coefficient for the Luminance_{MAX} of 100 cd/m² was the only statistically significant effect in the entire model. This indicates that increasing the JND/DDL value could improve contrast detection threshold up to a point (somewhere between 1.64 and 2.01 JNDs/DDL as shown in Table III for displays with Luminance_{MAX} of 100 cd/m² and Luminance_{MAX} of 200 cd/m²). Beyond 2.01 JNDs/DDL, the contrast detection threshold did not improve.

The background DDL did not have a substantial impact in these data as would be expected for a perceptually linearized display where the threshold detection of contrast change should be uniform across all the DDLs. The DICOM GSDF calibration, based on the Barten model of the HVS, should most closely create a perceptually linearized display for conditions of variable adaptation of the HVS.²² The CD detection threshold test for this study creates conditions for variable adaptation, and thus the display should be perceptually linearized and the contrast detection thresholds do not show a dependence on DDL. It is possible, however, that background DDL could have an impact with a different ambient light level. Phase II of this study investigated that possibility.

III.B. Phase II study

For simplicity, only data from the 22 pixel nodule is shown, elucidating the impact of lighting factors and display settings on the contrast detection thresholds. There was less of an impact for nodule size larger than 22 pixels, and a similar trend for nodule sizes smaller than 22 pixels.

Table VII contains the overall and one-dimensional conditional means for the contrast detection threshold. The reader should again recall that conditional means only describe the effect of a single listed variable and not the other listed variables. The identification threshold decreased as background DDL increased and as Luminance_{MAX} increased, but this is averaged across all room viewing conditions. The identification threshold was lower for the 30 lx ambient light conditions than for the viewing scenarios with 435 lx uncorrected (435U) and the 435 lx corrected (435C) conditions.

The authors fit a HLM in a similar fashion to Phase I of this study. Several models were explored, but the fixed-effects model with the main effects of background DDL, ambient light, and peak screen luminance (plus an interaction between background DDL and ambient light) was the final model selected. This model fit well compared to other potential alternative models, so its use is appropriate here. Table VIII contains a fit comparison of the unconditional and fixed effects model used, which, again, is an important check of model efficacy. The pseudo-*R* squared for this model was 0.24 ([2.40–

TABLE VII. Phase II overall and one-dimensional conditional descriptive statistics for identification threshold.

		Mean	SD
Overall threshDDL		5.6	1.7
Background DDL	50	6.0	2.1
	113	5.5	1.6
	176	5.4	1.6
	239	5.4	1.4
Ambient Light	30 lx	5.1	1.6
	435 lx U	5.9	1.9
	435 lx C	5.8	1.6
Luminance _{MAX} (cd/m ²)	400	5.1	1.6
	300	5.3	1.7
	200	5.4	1.6
	100	6.5	1.7

1.82)/2.40), which indicates that the HLM from this phase had substantially better prediction power.

Table IX contains the fixed effects for the Phase II HLM. The intercept condition for this model was a background luminance of 50 DDL, a display Luminance_{MAX} of 400 cd/m², ambient light of 30 lx, and nodule size of 22 pixels. The coefficients displayed represent the amount of change from the baseline condition when this condition was manipulated, assuming that all other factors were constant. The model-predicted mean threshold for the baseline condition was 4.65. To ascertain the effect from multiple variables, one would add the appropriate coefficients to the baseline condition in order to obtain the predicted mean for that condition. For example, a background DDL of 113 with 435 lx ambient, uncorrected for ambient light, and a Luminance_{MAX} of 100 cd/m² has a predicted mean of

$$\begin{aligned} &\text{Int.} + \text{BG DDL } 113 + 435 \text{ lx U} + \text{Lum}_{\text{MAX}} 100 \\ &\quad + (\text{BG DDL } 113 \text{ by } 435 \text{ lx U interaction}) \\ &= 4.65 - 0.19 + 1.90 + 1.39 - 1.00 = 6.75 \end{aligned}$$

It is important to note that the above example includes both the main effects and the interaction term for background

TABLE VIII. Phase II fit comparison of unconditional (null) and fixed effects model with likelihood ratio test for fit improvement.

Unconditional (null) model			Fixed effects (final) model	
Fit statistics			Fit statistics	
AIC	Log likelihood		AIC	Log likelihood
3258.1	−1626.1		3049.5	−1507.7
Random effects			Random effects	
Term	Variance		Term	Variance
Intercept	0.50		Intercept	0.52
Residual	2.40		Residual	1.82
Likelihood ratio fit test				
Model	df	Log likelihood	Likelihood ratio	<i>p</i>
Unconditional	3	−1626.1		
Fixed effects	17	−1507.7	236.6	<.001

DDL and ambient light. If the desired condition had contained the baseline factor level for either background DDL or ambient light, the interaction coefficients would not have been included in the calculation.

There are a variety of interesting effects occurring in this model. First, when the ambient light is at the baseline (30 lx), the background DDL does not appear to make a major difference, also seen in Table VI. If background DDL is at its baseline level of 50, both corrected and uncorrected 435 lx perform worse than at 30 lx (although 435 corrected is not quite statistically significant at the 0.001 level). As seen in Table III, both of these have lower realized $\Delta\text{JND}/\text{DDL}$ than for the 30 lx condition and at low DDL this is more severe in the uncorrected case. Correspondingly, the uncorrected 435 lx condition performs much worse than the baseline, as the detection threshold increases by 1.90 units. The differences from baseline associated with variation in luminance are non-significant until the luminance is 100 cd/m², where threshold performance degrades by 1.39 units. These effects are visually represented in Fig. 3, which is based on the combined coefficients from Table IX. Figure 3 shows two things: (a) the detection threshold dependence on maximum display luminance (variation within a curve) and (b) also a recovery in the detection threshold for the higher ambient condition when the calibration is corrected for the ambient light (variation between curves).

The coefficients related to background DDL in Table IX are more complicated. “Background DDL” taken alone applies to the baseline condition of 30 lx. In this case, there is no significant variation in the contrast detection threshold, as anticipated for a perceptually linearized display and as seen in Table VI. However, when the contribution for ambient light is

FIG. 3. Model-predicted detection threshold for a 22 pixel size spherical nodule conditional on maximum calibrated luminance and ambient light with 3.29 ($p < 0.001$) residual standard error bars, background DDL = 50. The different curves correspond to the following conditions: 435U = 435 lx without ambient light compensation, 435C = 435 lx with ambient light compensation in the calibration, and 30 = 30 lx without ambient light compensation.

TABLE IX. Phase II HLM fixed effects results. Intercept (baseline) condition = background luminance of 50 DDL, a display L_{MAX} of 400 cd/m^2 , ambient light of 30 lx, nodule size of 22 pixels.

HLM fixed effects condition		Coefficient	SE	df	<i>t</i>	<i>p</i>
Intercept		4.65	0.25	832	18.80	<0.001
Background DDL	113	−0.19	0.23	832	−0.86	0.391
	176	−0.14	0.23	832	−0.61	0.540
	239	0.19	0.23	832	0.86	0.391
Ambient light	435 lx U	1.90	0.23	832	8.40	<0.001
	435 lx C	0.65	0.23	832	2.88	0.004
Luminance _{MAX} (cd/m^2)	300	0.25	0.13	832	1.91	0.056
	200	0.36	0.13	832	2.73	0.007
	100	1.39	0.13	832	10.65	<0.001
Background DDL, ambient light 435 U interaction	113, 435 lx U	−1.00	0.32	832	−3.12	0.002
	176, 435 lx U	−1.53	0.32	832	−4.77	<0.001
	239, 435 lx U	−2.03	0.32	832	−6.33	<0.001
Background DDL, ambient light 435 C interaction	113, 435 lx C	0.07	0.32	832	0.22	0.828
	176, 435 lx C	0.13	0.32	832	0.39	0.697
	239, 435 lx C	−0.28	0.32	832	−0.87	0.386

Note: Coefficient = HLM fixed-effects coefficient (units are DDL), or change from intercept condition; SE = standard error; df = degrees of freedom; *t* = *t* coefficient testing the null hypothesis that the coefficient is 0, *p* = *p*-value corresponding to the *t* coefficient.

included, an interaction factor must also be added (along with the corresponding ambient light coefficient). This is discussed more thoroughly for Table X which provides the combined conditional coefficients for various conditions (Fig. 3).

In order to properly interpret what is happening with the ambient lighting factor, one must compare the conditionally combined coefficients for background DDL, ambient lighting, and their interaction for each relevant condition. Simply looking at the interaction coefficients is misleading, as it disregards the main effects for each of the individual factors. Table X contains the combined conditional coefficients for background DDL and different scenarios with ambient lighting and calibration. The numbers in this table are the result of summing the appropriate coefficients from Table IX for a given condition. For example, summing the Table IX coefficients for background DDL 113, 435 lx uncorrected, and their interaction is 0.71 (−0.19 + 1.90 − 1.00 = 0.71).

TABLE X. Phase II change in conditional combined coefficients for background DDL and lux conditions. Intercept (baseline) condition = background luminance of 50 DDL, a display L_{MAX} of 400 cd/m^2 , ambient light of 30 lx, nodule size of 22 pixels.

Factor levels	Combined coefficient delta
Background DDL 50 and 30 lx	0.00
Background DDL 113 and 30 lx	−0.19
Background DDL 176 and 30 lx	−0.14
Background DDL 239 and 30 lx	0.19
Background DDL 50 and 435 lx, uncorrected	1.90
Background DDL 113 and 435 lx, uncorrected	0.71
Background DDL 176 and 435 lx, uncorrected	0.23
Background DDL 239 and 435 lx, uncorrected	0.06
Background DDL 50 and 435 lx, corrected	0.65
Background DDL 113 and 435 lx, corrected	0.53
Background DDL 176 and 435 lx, corrected	0.64
Background DDL 239 and 435 lx, corrected	0.56

The result from Table X is that background DDL makes a difference for an ambient light level of 435 lx uncorrected but not for 30 lx or 435 lx corrected. This makes sense because in both the low ambient and high ambient corrected scenarios the displays have been calibrated for perceptual linearity (meaning contrast detection threshold would not change with DDL). This is not the case for the high ambient, uncorrected scenario where the contrast threshold changes from equivalent to the 30 lx scenario at high DDL to significantly worse than the 30 lx conditions at low DDL, as predictable from the nonlinear relationship between luminance and contrast sensitivity for the human visual system.⁶ This is also shown in Fig. 4, which shows combined coefficients from Table X. As seen in Fig. 4, the contrast thresholds are relatively uniform across background DDL for the 30 lx and 435 lx corrected, where ambient light is low or has been accounted for in the display calibration. However, for the uncorrected, high ambient condition there is an increase in detection threshold for the darker (lower DDL) backgrounds.

To understand why the uncorrected high ambient case has a lower detection threshold than the corrected one at high DDL, it is helpful to consider $\Delta\text{JND}/\text{DDL}$ relative to background DDL for the two cases. Recall from Tables VI and IX a correlated improvement in detection performance with increasing JND/DDL until somewhere between 1.64 ($L_{\text{MAX}} = 100 \text{ cd/m}^2$) and 2.01 JND/DDL ($L_{\text{MAX}} = 200 \text{ cd/m}^2$). Below that threshold, increasing $\Delta\text{JND}/\text{DDL}$ appears to improve the contrast detection threshold. For the case of high ambient light, the JNDs/DDL has the greatest decrease for low DDL. The reduction in JNDs/DDL is most significant for a low luminance display. For example, in high ambient conditions the realized $\Delta\text{JND}/\text{DDL}$ for DDL 50 is ~ 1.1 for L_{MAX} of 100 cd/m^2 . When the display calibration is corrected for the ambient light, the $\Delta\text{JND}/\text{DDL}$ around DDL 50 increases to 1.4 for L_{MAX} of 100 cd/m^2 . This increase in JND/DDL is in the range where it appears to

FIG. 4. Model-predicted detection threshold for a 22 pixel object conditional for various background DDL and ambient light conditions with 3.29 ($p < 0.001$) residual standard error bars, maximum calibrated luminance = 200 cd/m^2 .

improve detection. But at higher background DDLs, this gain in JND/DDL between uncorrected and corrected displays is not seen. For example the $\Delta\text{JND/DDL}$ at DDL 239 is 1.6 for uncorrected displays and 1.4 for corrected displays. The ambient light compensation in essence redistributes the JNDs over the luminance range to achieve perceptual linearity, increasing it for low DDL and decreasing it for high DDL. With this in mind it makes sense that:

- Ambient light compensation improved the contrast detection threshold for low DDL relative to the uncorrected case (0.65 vs. 1.90 in Table X).
- Contrast detection threshold is nearly constant across DDL for ambient light compensation which creates a perceptually linear display.
- And performance is better when the background ambient lighting is lower, as demonstrated by the consistently low coefficients for the 30 lx conditions.

IV. DISCUSSION

Recall the motivation for this work was to understand optimal display settings in both reading room and clinical (higher ambient) environments based on the contrast detection thresholds. This understanding is needed in order to justify the added expense of requiring a higher luminance display setting, or added effort in adjusting the settings of a display for a clinical ambient setting. This study used human observers with computer generated spherical nodules on solid backgrounds. It is a simplified model that lacks the luminance background variation that would be present with a patient image but helpful for elucidating general settings for general tasks and providing a magnitude for the effects of certain variables on contrast detection thresholds. This information

can be used to provide optimized display settings (for generic tasks) for different fixed lighting conditions.

We acknowledge there are differences between our experiment involving the serial search for the known presence of single objects on a uniform background and the conditions of a visual search in an actual medical image. While task based imaging studies are warranted and interesting, we are also looking for multipurpose solutions for display settings which could be relevant beyond any specific image example or example set. We hope our findings add value to the field just as they have aided in our own determination of display settings for our practice. We acknowledge the complexity of the HVS which limits our ability to find a perfect setting, or calibration that would fit a wide-range of image display and environmental variables.

Other techniques for managing ambient light include raising the minimum luminance either alone or in conjunction with a calibration which factors in ambient light to each DDL. Different ambient compensation techniques were not compared in this study. Simply raising the minimum luminance does not fully recover the perceptual uniformity of the Barten model, but it does eliminate the most severe loss of JND at low DDL and makes the calibration more robust to smaller fluctuations in ambient lighting which may be typical of reading rooms. This may also be of benefit in considering adaptive shifts in the HVS to higher luminance.¹¹ Raising the minimum luminance can be relatively easily accomplished. Creating custom calibration LUTs which take into account ambient light is more difficult when the commonly used contact photometer puck is employed and a true ambient compensating calibration is not readily available with the vendor calibration software.

V. CONCLUSIONS

We recall the goals of this study and provide the related results:

- What is the optimal maximum luminance setting for either low or high ambient viewing conditions with a fixed minimum luminance (black level) of 0.5 cd/m^2 ?

There was a statistically significant difference in performance between $\text{Luminance}_{\text{MAX}} = 100 \text{ cd/m}^2$ and 200 cd/m^2 for all ambient conditions. This represents an increase from 1.62 to 2.01 JND/DDL at 30 lx and from 1.37 to 1.74 JND/DDL for the ambient light corrected case at 435 lx (from Table III). While the data showed a slight decrease in detection threshold for higher $\text{Luminance}_{\text{MAX}}$, this change was not significant. In our HLM model of the data, no significant interaction was found between maximum luminance and ambient light, meaning that the increase in luminance did not necessarily create greater benefit for the higher ambient light. Perhaps for all ambient cases (at least at the higher DDL), the change between 100 and 200 cd/m^2 was sufficient to cover the “sweet spot” of improvement in detection threshold. Or, perhaps, our study was not strong enough to capture this effect.

2. Using the same display calibration setting as for question 1 (with no ambient light compensation), what is the effect on contrast discrimination thresholds with higher ambient lighting conditions?

There is a significant increase in the detection threshold with higher ambient lighting for low DDL (when no ambient light correction is employed). This effect is negligible for higher DDL, as expected from the Barten model. The increase in threshold is shown in Tables IX and X and Fig. 4. This change in detection threshold inversely mirrors the change in calculated JND/DDL for the high ambient case, as given in Table III which shows that JND/DDL varies from 0.78 to 2.43 JND/DDL when ambient light of 435 lx is present.

3. What is the effect on the contrast discrimination threshold if the display is recalibrated to compensate for higher ambient light (in concordance with the DICOM GSDF)?

A primary result of the recalibration is that there is greater uniformity in detection threshold across the gray scale (i.e., different DDL background). This inversely mirrors the change in JND/DDL for a given DDL with different ambient and calibration conditions. As shown in Table III without correction for ambient light (435 lx), the calculated JND/DDL vary between 0.78 and 2.43 JND/DDL for the case of $L_{MAX} = 400 \text{ cd/m}^2$. With correction for the high ambient light (435 lx) and with the same $L_{MAX} = 400 \text{ cd/m}^2$ the JND/DDL is uniform at 2.13 JND/DDL for all DDL. With correction, there is a significant improvement for low DDL in the detection threshold with the ambient light correction in the calibration (see Fig. 4), however, the benefit is reversed at high DDL.

The notion of looking at realized JND/DDL and aiming for this JND/DDL “sweet spot” correlates well with the contrast detection threshold data presented in both phases of the study. Looking at realized JND/DDL values for the different displays and conditions shows that the process of recalibrating displays for higher ambient lighting can redistribute JNDs over the range of DDL, regaining significant losses at low DDL and because the HVS is nonlinear the JND loss at higher DDL is less significant.

ACKNOWLEDGMENT

This study was partially developed while Dr. George C. Kagadis was a Fulbright research scholar to the Radiology Informatics Lab within the Radiology Department at Mayo Clinic, Rochester, MN.

^{a)}Author to whom correspondence should be addressed. Electronic addresses: gkagad@gmail.com and George.Kagadis@med.upatras.gr; Telephone: +30 2610 969146; Fax: +30 2610 969166.

¹FDA, “Mammography Quality Standards Act and Program,” <http://www.fda.gov/radiation-emittingproducts/mammographyqualitystandardsactandprogram/default.htm> Accessed on June 13, 2012.

- ²MQSA, “Mammography Quality Standards Act of 1992. Public Law 102-539. As amended by the Mammography Quality Standards Reauthorization Act of 1998, Pub. L. No. 105-248, Title 42, Subchapter II, Part F, Subpart 3, §354 (42 USC 263b), certification of mammography facilities” (1992).
- ³ACR, *Mammography Quality Control Manual* (American College of Radiology, Reston, VA, 1999).
- ⁴W. Breeden and J. Norbeck, “ACR Technical Standard for Electronic Practice of Medical Imaging” (2007).
- ⁵ACR, “ACR–AAPM–SIIM Technical Standard for Electronic Practice of Medical Imaging” 2012.
- ⁶P. G. J. Barten, *Contrast Sensitivity of the Human Eye and Its Effects on Image Quality* (SPIE, Bellingham, WA, 1999).
- ⁷DICOM, “Digital Imaging and Communications in Medicine (DICOM), Part 14: Gray Scale Standard Display Function,” Rosslyn, VA, 2004.
- ⁸ACR, “2004 Magnetic Resonance Imaging Quality Control Manual” (ACR, Reston, VA, 2006).
- ⁹ACR, “American College of Radiology Technical Standard for Electronic Practice of Medical Imaging” (2007).
- ¹⁰P. C. Brennan, M. McEntee, M. Evanoff, P. Phillips, W. T. O’Connor, and D. J. Manning, “Ambient lighting: Effect of illumination on soft-copy viewing of radiographs of the wrist,” *AJR, Am. J. Roentgenol.* **188**, W177–W180 (2007).
- ¹¹A. S. Chawla and E. Samei, “Ambient illumination revisited: a new adaptation-based approach for optimizing medical imaging reading environments,” *Med. Phys.* **34**, 81–90 (2007).
- ¹²C. M. Park *et al.*, “Comparison of observer performance on soft-copy reading of digital chest radiographs: High resolution liquid-crystal display monitors versus cathode-ray tube monitors,” *Eur. J. Radiol.* **66**, 13–18 (2008).
- ¹³B. J. Pollard, A. S. Chawla, D. M. Delong, N. Hashimoto, and E. Samei, “Object detectability at increased ambient lighting conditions,” *Med. Phys.* **35**, 2204–2213 (2008).
- ¹⁴P. Sund, M. Bath, and L. G. Mansson, “Investigation of the effect of ambient lighting on contrast sensitivity using a novel method for conducting visual research on LCDs,” *Radiat. Prot. Dosim.* **139**, 62–70 (2010).
- ¹⁵M. Uffmann, M. Prokop, W. Kupper, T. Mang, V. Fiedler, and C. Schaefer-Prokop, “Soft-copy reading of digital chest radiographs: Effect of ambient light and automatic optimization of monitor luminance,” *Invest. Radiol.* **40**, 180–185 (2005).
- ¹⁶E. Samei *et al.*, “Assessment of display performance for medical imaging systems: Executive summary of AAPM TG18 report,” *Med. Phys.* **32**, 1205–1225 (2005).
- ¹⁷P. G. J. Barten, “Formula for the contrast sensitivity of the human eye,” *Proc. SPIE* **5294**, 231–238 (2004).
- ¹⁸J. Wang, J. Xu, and V. Baladandayuthapani, “Contrast sensitivity of digital imaging display systems: Contrast threshold dependency on object type and implications for monitor quality assurance and quality control in PACS,” *Med. Phys.* **36**, 3682–3692 (2009).
- ¹⁹J. Wang, K. Compton, and Q. Peng, “Proposal of a quality-index or metric for soft copy display systems: Contrast sensitivity study,” *J. Digit Imaging* **16**, 185–202 (2003).
- ²⁰J. Wang and Q. Peng, “An interactive method of assessing the characteristics of softcopy display using observer performance tests,” *Proc. SPIE* **4686**, 189–197 (2002).
- ²¹S. W. Raudenbush and A. S. Bryk, *Hierarchical Linear Models: Applications and Data Analysis*, 2 ed. (Sage Publications, Thousand Oaks, CA, 2002).
- ²²E. Samei, “AAPM/RSNA physics tutorial for residents: Technological and psychophysical considerations for digital mammographic displays,” *Radiographics* **25**, 491–501 (2005).
- ²³J. M. Herron, T. M. Bender, W. L. Campbell, J. H. Sumkin, H. E. Rockette, and D. Gur, “Effects of luminance and resolution on observer performance with chest radiographs,” *Radiology* **215**, 169–174 (2000).
- ²⁴M. Ikeda *et al.*, “Influence of monitor luminance change on observer performance for detection of abnormalities depicted on chest radiographs,” *Invest. Radiol.* **38**, 57–63 (2003).
- ²⁵J. M. Goo *et al.*, “Effect of monitor luminance and ambient light on observer performance in soft-copy reading of digital chest radiographs,” *Radiology* **232**, 762–766 (2004).
- ²⁶S. Hidano, M. Ikeda, T. Ishigaki, H. Usami, K. Shimamoto and K. Kato, “Effects of monitor luminance change on observer detection performance,” *Comput. Med. Imaging Graph.* **29**, 35–41 (2005).