A Brief Review of Human Perception Factors in Digital Displays for Picture Archiving and Communications Systems

Jihong Wang and Steve Langer

The purpose of this review is to further inform radiologists, physicists, technologists, and engineers working with digital image display devices of issues related to human perception. This article will briefly review the effects of several factors in human perception that are specifically relevant to a digital display environment. These factors include the following: the spatial and contrast resolution of the display device; background luminance level and luminance range of the display system; brightness uniformity; extraneous light in the reading room; displayed field size; viewing distance; image motion and monitor flickering; signal to noise ratio of the displayed image; magnification functions; and the user interface. After reviewing the perception study results, a checklist of desirable features and quality assurance issues for a digital display workstation are presented as an appendix.

KEY WORDS: picture archiving and communications systems (PACS), quality assurance/control, visual perception, evaluation.

RAPID DEVELOPMENTS in digital image acquisition and display technology raise concerns as well as interesting discussions about quality assurance, quality control of display devices, and viewing conditions in a digital display environment.[1-4] For instance, computed radiography (CR) can provide a dynamic range wider than that which current computer monitors can resolve.[5] Consequently the optimal display algorithm and look up tables (LUT), as well as the viewing conditions, will directly affect lesion detection from a monitor.[1-3] Furthermore, viewer performance may depend on other factors such as monitor resolution, masking extraneous light (eg, the reflection of light from the monitor), monitor brightness, and so on.[3] Optimal interface design and quality assurance of workstations, including their environment, should provide a high quality and efficient work area for radiologists and technologists.[1] In addition, user-friendly workstations reduce personnel training costs. It may also minimize user fatigue and errors.

In this review, the perception issues relevant to evaluating a digital display workstation and those factors that should be monitored and controlled to assure the optimal function of the workstation are discussed. The checklist presented in Appendix 1 provides a useful starting point for decision making and evaluation in picture archiving and communication systems (PACS) acquisition. The tasks radiologists perform during the reading room session are observed. Specifically these tasks involve human eye perception and its interaction with workstation design and viewing conditions. Then, published data related to human perception in detecting objects under various conditions are reviewed. Those factors relevant to image display systems used in radiology are then analyzed. These results and their relevance and implications in the digital radiology department are discussed. The perception factors to be discussed in this review are limited to those that are controllable and relate to the design of workstation and viewing conditions.

PERCEPTION TASKS

The tasks observers perform during reading room sessions (either using a viewbox or a computer workstation) are depicted schematically in Fig 1. Figure 1 shows the functional work flow in a reading room. The tasks that may be relevant to visual perception are marked in the blocks. Some of these factors may have a greater effect on some observers than others.

In such a reading room session, the radiologist's task usually involves the following: (1) quality check of the image, (2) searching for new lesions or abnormalities, (3) "surveillance" of preexisting abnormalities and assessment of changes, (4) interpretation of the new findings, (5) reporting, (6) measurement of the new findings, if necessary, and (7) detailed analysis of the new findings and documenting them.

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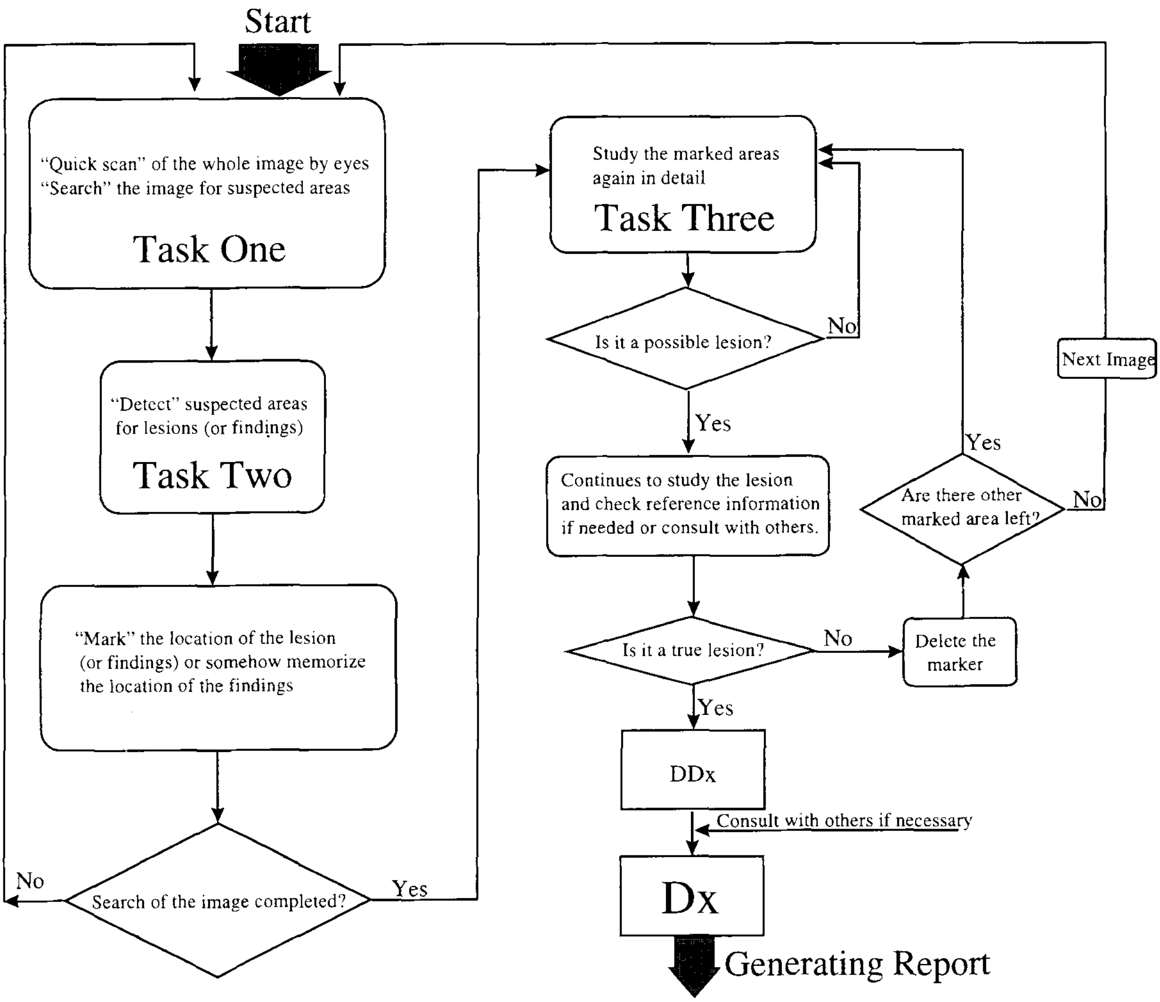

Fig 1. Work flow in a reading room and tasks relevant to perception.

PERCEPTION FACTORS

Based on the perception tasks involved in the reading room session, some relevant perception factors which may affect observers' performance are (1) spatial and contrast resolution of the display device; (2) brightness and the displayed luminance range of the monitor (or film/viewbox); (3) uniformity of the display system luminance; (4) extraneous light in the reading room (such as bright, unmasked areas on the monitor and light reflected off the monitors); (5) displayed field size (field of view); (6) viewed object orientation; (7) image motion and flickering of display device; (8) signal to noise ratio of the displayed image; (9) magnification and zooming functions; and (10) user interface of the workstation. These factors will be discussed in turn.

Spatial and Contrast Resolution of the Display Device

In general, the smaller an object, the less visible it is. However, neither contrast nor size alone determine if an object is visible. To be seen, an object has to exceed physiological thresholds both in size and contrast.[6] Figure 2 shows the contrast threshold as function of object size. The chart indicates that as the object size decreases, the minimum visible contrast level increases. This means that an object needs higher contrast to be seen. This chart also depicts detection thresholds

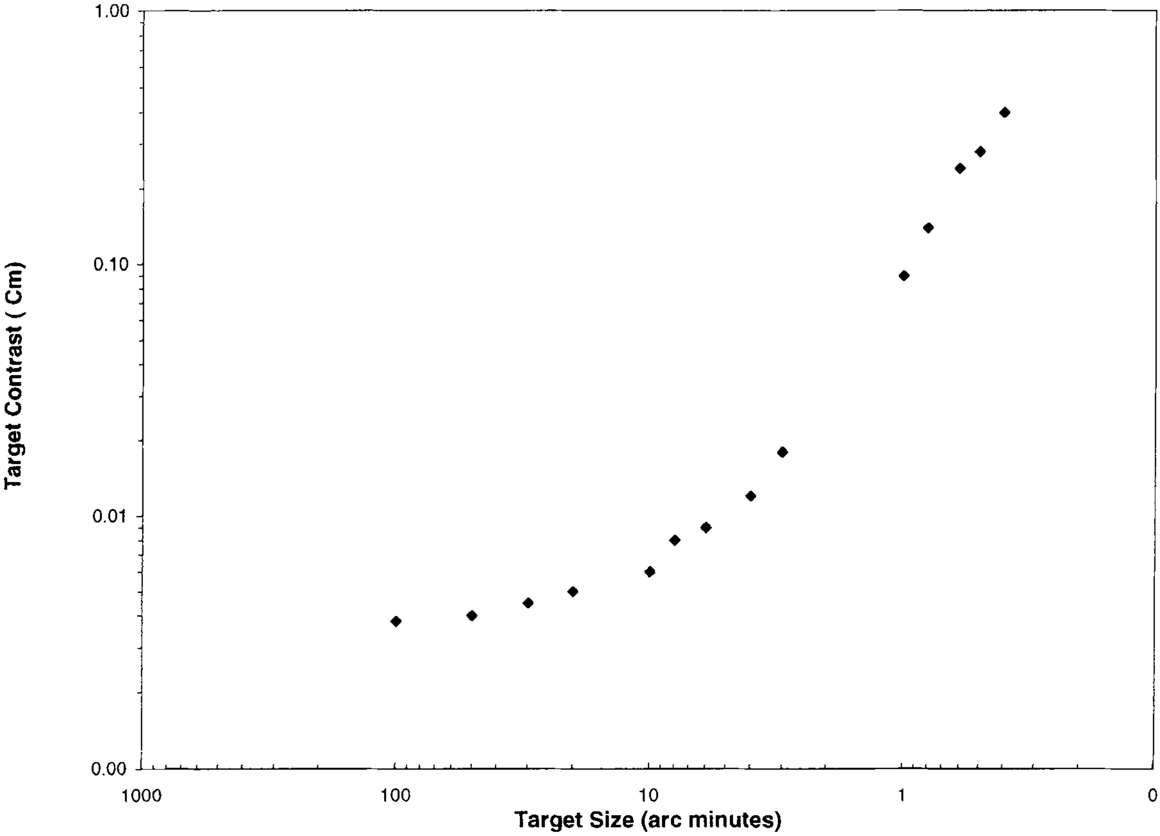

Fig 2. The human eye's contrast sensitivity for disk targets of different sizes (replotted based on data from reference 6).

for both size and contrast. These curves are often referred as the Contrast-Detail curves. However, the absolute value of contrast and detail sensitivity depends on many other factors including the brightness of targets and the shape and background of the target.[6]

In the film/viewbox display system, spatial resolution is limited to the resolution of the screen-film system. In a digital display environment, however, spatial resolution is determined by both detector and monitor resolution. Most commercially available monitors have 1,000 (1K) or 2,000 (2K) lines of resolution.[3] 2K monitors are more expensive than 1K monitors. The width of the monitor scan line determines the spatial resolution of the monitor.[3] The thinner the scan line is, the higher the spatial resolution. Compared to film, the spatial resolution of the monitor is inferior, even for the 2K monitors.[3] On the other hand, most of the computer system can "magnify" the digital image all the way to the individual pixel; therefore, the spatial resolution is limited by the digital acquisition modality rather than by the display system.

The spatial resolution of the monitor is more important for digital images with large matrix size, such as computed radiography (CR). For these types of images, the monitor resolution is particularly relevant when the whole image is displayed on the monitor. In a digital display system, the contrast and size of object can be adjusted to a certain degree by windowing and leveling, and by magnification, which somewhat compensates for losses in spatial resolution. In addition, one study has already indicated that readers find the convention screen-film radiographs, laser film of CR images and cathode ray tube (CRT) displays nearly equivalent although the films on a viewbox is still favorable.[7]

Human eyes have another interesting characteristic regarding contrast sensitivity as a function of spatial frequency for cyclical targets.[8-10] If the contrast sensitivity versus the spatial frequency of a typical human eye is plotted, the contrast threshold versus spatial frequency curve for cyclical targets can be shown as in Fig 3. Note that the minimum in the contrast threshold (greatest perceptual sensitiv-

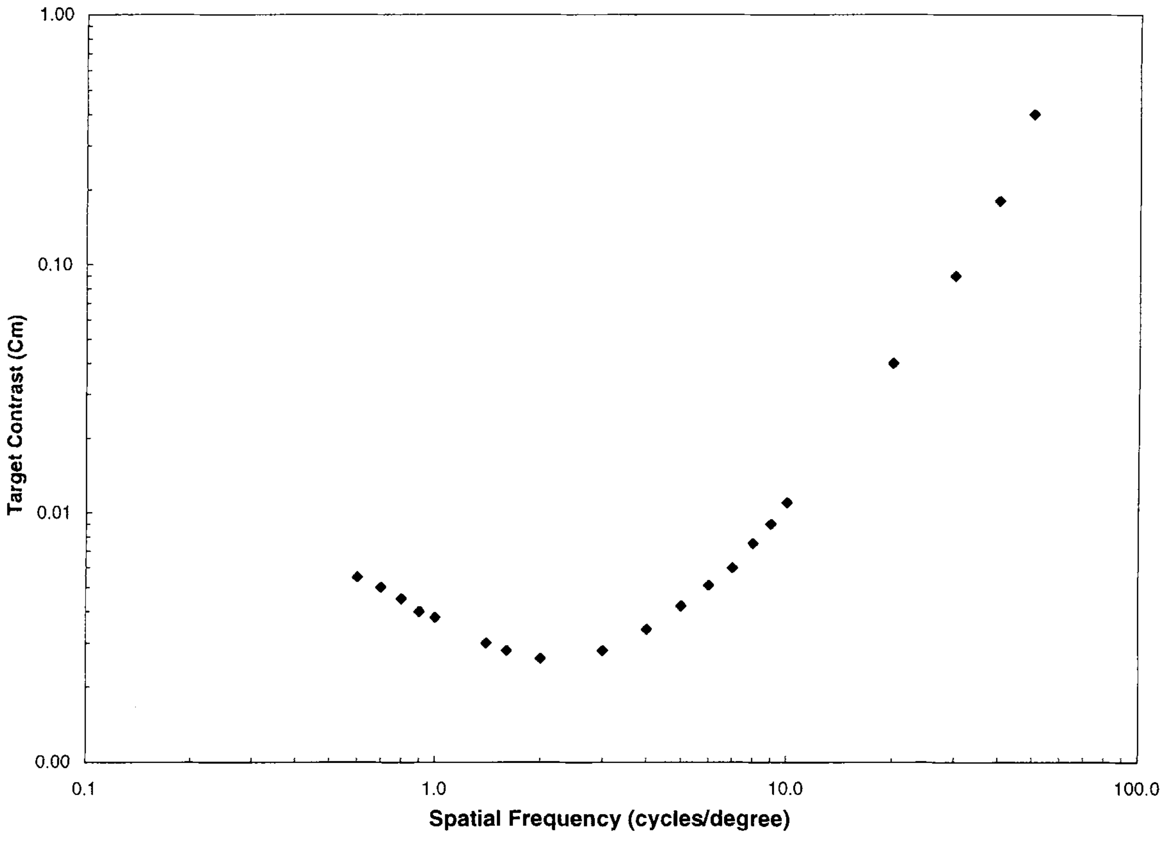

Fig 3. The human eye's contrast sensitivity versus spatial frequency (replotted based on data from references 9 and 10).

ity) occurs at 2 to 3 cycles per degree. This corresponds to a spatial frequency of 5 line pairs per cm (or, about 1 mm wide pixels). For comparison, current CR systems have a pixel size of about 0.3 mm.[5] Figure 3 shows that human eyes are most sensitive to 1 mm pixel size for a target with a sinusoidal contrast pattern viewed from a 25 cm distance, and become less sensitive to smaller or bigger pixel sizes. This implies that there may be an optimal viewing distance for certain types of monitor design and for certain types of displayed images.

Brightness and Luminance Range of the Monitor (or Film/Viewbox)

Previous studies have shown that contrast sensitivity of human eyes increases as the luminance of an object increases.[11,12] As shown in Fig 4, the higher the background luminance level, the more sensitive the human eye becomes. Also, perceived image quality has a direct relationship with the luminance level of the image. One study showed that the perceived image quality increases as the luminance of the illuminator increases.[13] Figure 5 indicates the perceived image quality versus the luminance of the display. The image is perceived as better quality with higher luminance. The perceived image quality continues to improve up to approximately 3,500 nit (1 nit = 1cd/m^2).[13] The curve then drops beyond 6,000 nit perhaps because of excessive glare.

At present, luminance levels of most computer monitors are much lower compared to those of viewboxes that usually have luminance levels around 3000 nit.[3] Some PACS vendors have higher luminance (500-600 nit) monitors available but these types of monitors are more expensive.

Figure 4 indicates that there is still improvement in contrast sensitivity for increases in target luminance, even when the luminance level goes from 3,400 to 10,000 nit. But the last threefold increase in luminance reduced the contrast threshold only by 5%, from 0.038 to 0.036. At lower luminance levels, however, increases in luminance can substantially improve the contrast sensitivity of human eyes. For digital display environments where moni-

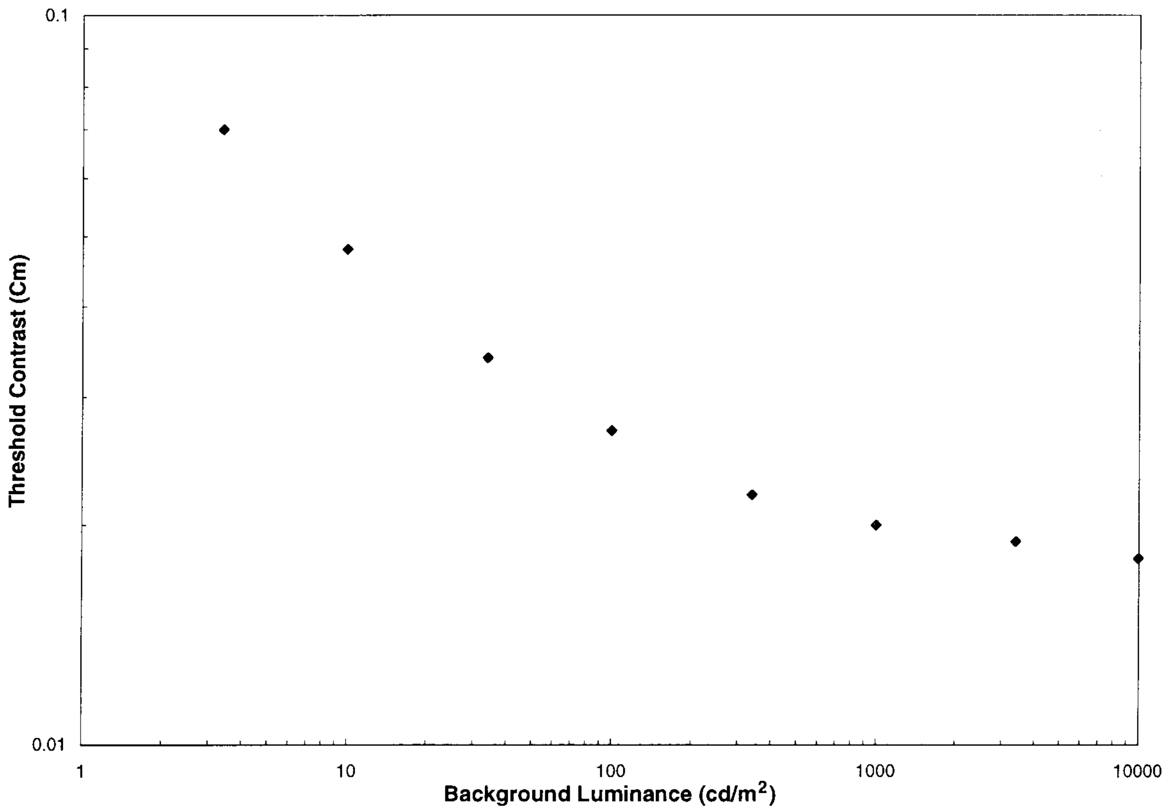

Fig 4. The human eye's contrast sensitivity versus luminance level (replotted based on data from reference 12).

tors are used, the luminance level becomes important because the variance in monitor luminance can make a significant difference in the contrast sensitivity of human eyes.

Not only is the absolute level of luminance important, but also the range of luminance levels that a device can display. The dynamic range of a CRT is narrower than the optical density range of film displayed on a viewbox.[3] The dynamic range of a display should be an factor to consider when comparing monitor quality for a PACS.

When purchasing a digital display workstation, it is important to evaluate the luminance level the monitors can provide. The stability of the luminance level is the other specification one should consider. A good monitor should be bright and stable over time.

Uniformity of the Monitor

The uniformity of monitor luminance and resolution are important to guarantee the contrast/detail uniformity across the whole display field of view. In the film/viewbox environment as well as the computer-monitor environment, it is desirable to have the same contrast sensitivity across the entire displayed field of view. A monitor with a nonuniform luminance level may result in missing low contrast objects in the displayed image, although the uniformity of a CRT display device is better than that of a viewbox.[3]

Extraneous Light in the Reading Room and Reflection of the Monitors.

Previous studies on the film/viewbox display system have shown that viewing conditions such as extraneous light have a significant effect on the performance of viewers.[14-17] In one of our own studies,[17] the effect of masking the extraneous light in mammography films was studied. Using a contrast-detail phantom and a high luminance viewbox (8,000 nit), the detection of small, low-contrast objects on mammography films viewed by 8 viewers with a masked viewbox was compared to those viewed without an unmasked viewbox. Studies were performed for various film densities. The results (Fig 6) showed that viewbox masking significantly affects the ability to detect low contrast objects, comparable to the similar studies

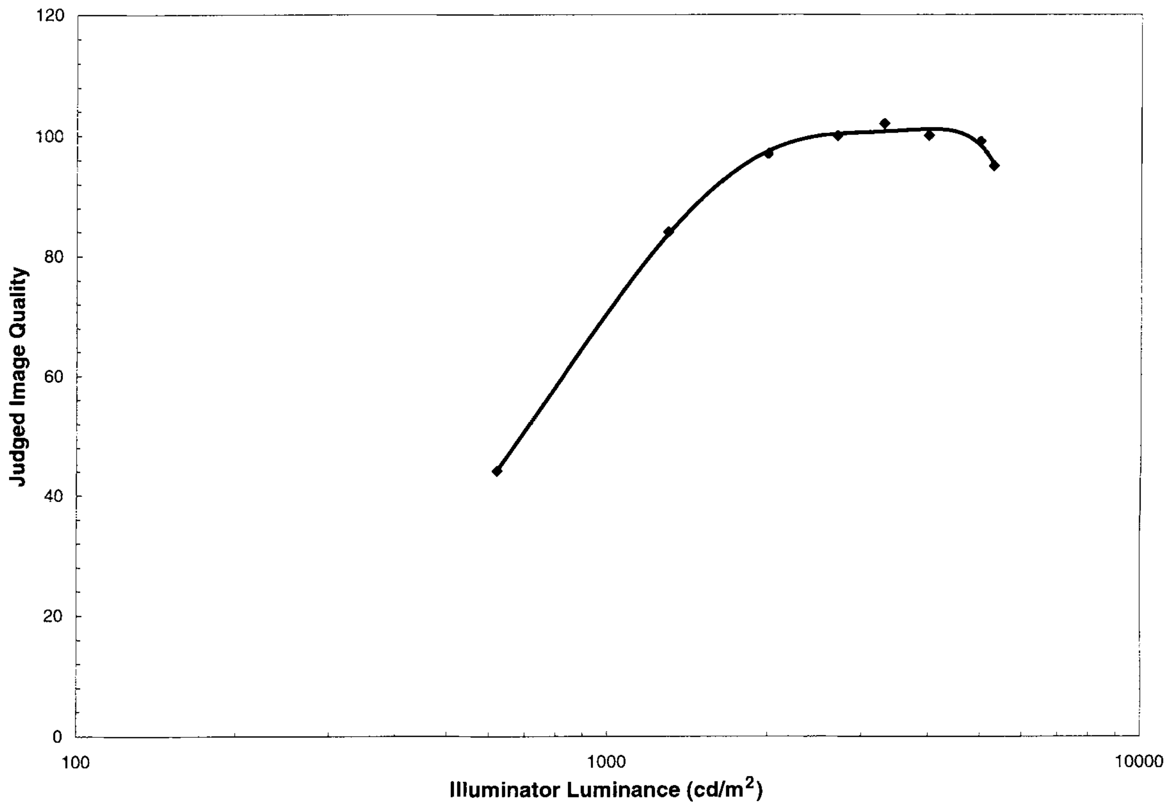

Fig 5. Perceived image quality and luminance level (replotted based on data from reference 13).

reported previously.[14-16] Extraneous light in the reading room decreases the perceived object contrast, thereby decreasing the ability of human eyes to detect these objects. Elimination of extraneous light by masking the film therefore noticeably improves viewer's ability to detect small objects.

Figure 6 depicts the minimum detectable size ratio (MDSR) versus object contrast. The MDSR was defined as the diameter of the smallest visible object viewed with an unmasked viewboxes (with extraneous light) versus the diameter of those viewed with masked viewboxes (no extraneous light) at the same object contrast level. Therefore, at any contrast level, an MDSR larger than 1 means that the observer can see smaller objects at the same contrast level with masked viewboxes, ie, have better performance.

As also shown in Fig 6, as the film density increases, the difference in MDSR becomes more significant. For example, with film density at 2.27 optical density (OD), the viewer can see objects that are 40% to 80% smaller in size using the masked viewbox compared to those using an unmasked viewbox. This indicates that one should view films with masked viewboxes. In the digital display environment, the effect of extraneous light will be very significant since the luminance level of the monitor is substantially lower than that of the viewbox, and the reflection off the monitor further diminishes contrast. The monitors should be properly masked from the extraneous light in the reading room. To further reduce extraneous light, it is desirable for the user interface of the computer software to set the blank areas on the digital image at the lowest luminance level. The designers of the workstation environment must consider the computer display monitor carefully.[1]

Displayed Field Size (Field of View)

The effect of display field size has not been an important issue in the film/viewbox display system because the size of the display field (which is the size of the film) is fixed by default. In the monitor display system, however, things are different. Everyone with a computer can tell you how nice and comfortable it feels to have a bigger monitor, but what are the psychological reasons behind this "comfort"?

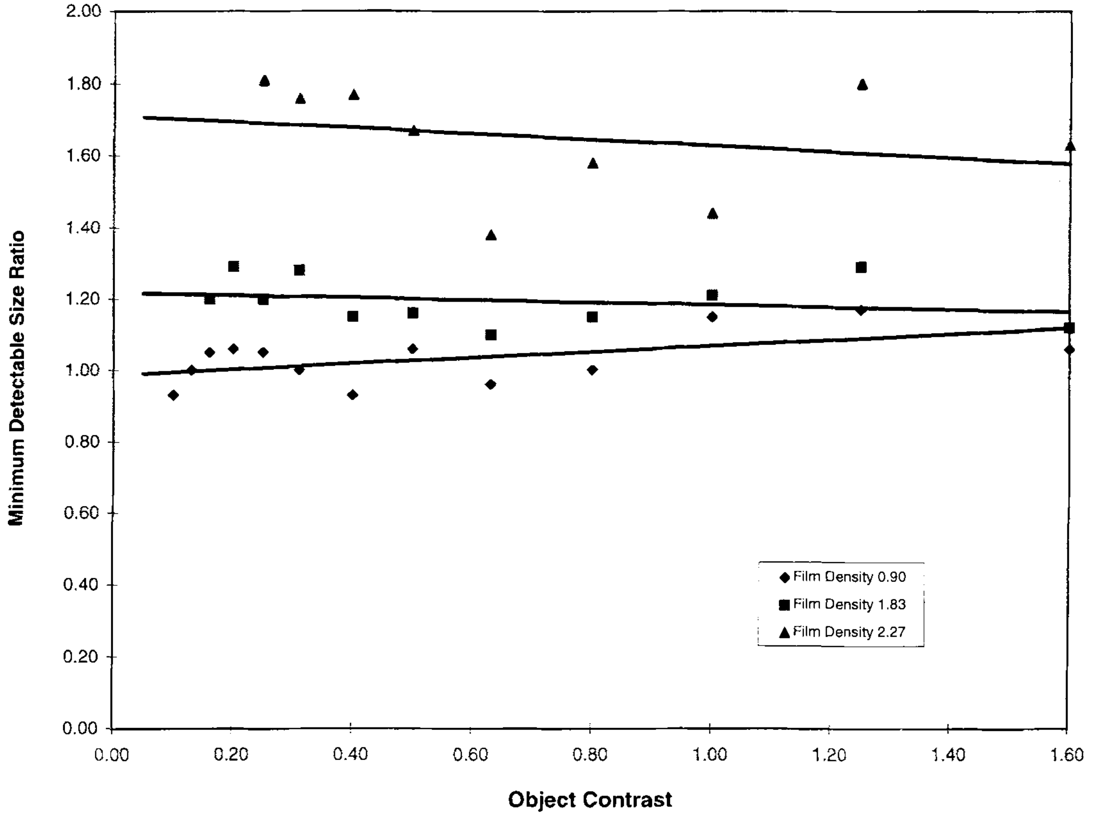

Fig 6. Effect of extraneous light on the minimum detectable object size. The minimum detectable object size ratio (unmasked viewbox versus masked viewbox) plotted as a function of the object contrast (in disk thickness). A minimum detectable object size ratio greater than 1.0 means that one can see smaller objects of the same object contrast with the masked viewboxes compared to the unmasked viewboxes. The effect of masking increases as the film density increases. The lines represent the best fit for films with densities of 2.27, 1.83, and 0.90 respectively. Statistical analysis shows that there is significant improvement in object detection for film densities at 1.83 and 2.27 ($P < .01$) but not for film density at 0.90. (Data from reference 17.)

A larger field size helps the observer to see enough area at a glance to understand all the components of the targets in context. Since the eyes can be redirected faster than the image can be repositioned by any imagery display system, a bigger displayed field of view facilitates quicker inspection of all areas on an image. Too small a display field may cause lower performance, and lower search efficiency.[18] It may also cause the undesirable sensation of tunnel vision which, over a long period of time, may cause discomfort and result in decreased performance. However, too large a display field can be very costly. Distortion at the peripheral of the field of view is unavoidable. This leads to missing a higher proportion of areas that could be overlooked. Five to 10° of visual field may be too small. Yet, a field larger than 60° make it difficult to turn the head.

Figure 7 shows significant improvement in performance as display field size increases from 20° to 40°.[18] Yet there seems to be no improvement in search performance as the image field size is increase beyond 54°. Only a small, insignificant increase in performance is seen as the field size is increased from 36° to 54°. Ideally, determination of display field size should be based on an understanding of how information concerning an image is received and processed by the user. It may be interesting to quantitatively study the effect of monitor size and viewing distance in a PACS workstation. Changing viewing distance varies the effective display field size. As the viewing distance decreases the effective display field size increases.

Viewed Object Orientation

In the conventional film/viewbox display system, the orientation of the displayed image can be easily adjusted and even predefined by the shape of the film. Films usually have a rectangular or square

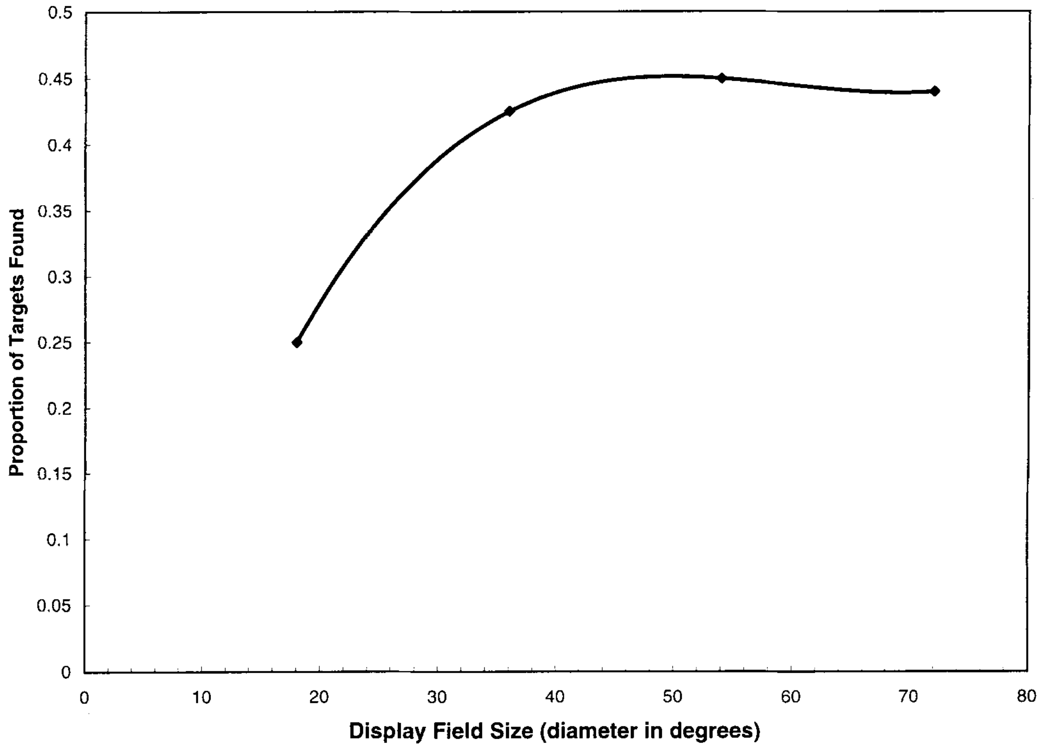

Fig 7. Performance versus display field size (replotted based on data from reference 18).

shape. The spatial resolution of the film is nearly isotropic. This isotropic character does not hold in the monitor display.

It is known that the display orientation of the object may affect the perception of human eyes. Previous studies have shown that grating objects in both the horizontal and vertical orientation are easier to see than those in an oblique angle.[19,20] This phenomenon has its immediate relevancy to the digital image display system in which the spatial resolution is intrinsically anisotropic. For example, a subtle edge may or may not be detectable depending on the orientation of the linear edge. Unfortunately, there is not a lot of literature published or available on this topic for CRT display device. The effects of the image display orientation on the computer monitor needs further study.

Image Motion and Display Flicker

To view a moving image, observers must attempt to reduce the effect of the motion by tracking the image with their eyes during each fixation period. The image motion and monitor flicker becomes a relevant issue in the display system because flickering and subtle motion of the whole image on the monitor reduces contrast sensitivity and causes undesirable sensations in some viewers.[21] Human eye contrast sensitivity decreases when the whole image is in motion.[21] However, the relationship between contrast sensitivity and the image motion velocity depends on many variables, eg, the amount of the time available to look at each particular area in the image.[22]

For most of the modern CRT display devices, obvious motion of displayed static image is not a problem. However, flickering of the monitor is not an uncommon phenomenon. It is not only annoying, but may also decrease the performance and potentially decrease contrast sensitivity of the observer. Standards or guidelines that address this issue are needed.

Signal-to-noise Ratio of the Displayed Image

A higher signal-to-noise ratio always makes an object more visible. Display noise is the fluctuation in luminance (spatially and temporally) that occurs when the electronic signal is constant.[3] The temporal noise may be caused by the electronic circuits in the CRTs, variations in the electron beam or in the beam deflection circuits, or problems in the digital-to-analog conversion.[3] The spatial noise is the luminance fluctuation caused by the granularity of monitor phosphor, which directly determines the contrast resolution of the CRT display. Although the signal-to-noise ratio of a monitor is not the "weak link" in the imaging chain, it is still desirable to have high signal-to-noise ratio in the display system. One should always compare the specifications of the monitors when purchasing a digital display system.

The Effect of Magnification

Magnification can sometimes help to make an object visible. The effect of magnification is to increase the visual angle subtended by a small object so that the viewer can see that object. The goal of increasing display magnification is to shift the modulation sensitivity curve of the eye/display combination in the spatial frequency domain of the object specified by the amount of the magnification.

It is generally believed that continuous zooming is better than discrete magnification, partially because the location of the image does not move at the fixation point. Thus the magnified image location is more predictable and does not block sight of the image. Also, the brain does not have to reprocess the image again; it can concentrate on the details in the image.

In the digital display environment, the limit to magnification is not (as in optical systems) the diffraction limit, but rather the limit under which individual pixels are visible. The magnification beyond that does not provide additional visibility. In fact, a too "pixelly" image is undesirable to many viewers.

User Interface Design

The user interface design of a monitor display system is crucial for its acceptance in a clinical environment. It has to be accepted by the end users, usually the radiologists. Unfortunately, it is sometimes considered to be of secondary importance by some of the PACS workstation designers. Horii has thoroughly discussed the ergonomic issues as well as the user interface design in PACS.[1] The reader can refer to that article for further details.

A good user interface should at least have the following features:

- Follow a standard user interface such as MS Windows (Microsoft, Redmond, WA), X-windows, or Macintosh (Apple Computer, Cupertino, CA) based designs.
- Be intuitive to use (for example, by using conventional icons representing repetitive functions).
- Be customizable to the individual user's preferences for viewing images.
- Display parameters such as the look up tables (LUT) should be optimized according to image type, exam type, and so on.
- Be easy to compare images of previous exam and current exam.
- Be easy to put images into a variety of display formats.
- Allow user to easily move images onto different monitors.
- Allow user easily rotate, flip, change contrast/ brightness of images.

RECOMMENDATIONS

Based on these factors, one can conclude that it is desirable to have multiple monitors with high spatial resolution (2K for plain film radiographic exams, and at least 1K for MRI and CT exams), high level of luminance, and uniformity. It is crucial to have optimized viewing conditions in a digital-based display system. Issues such as proper lighting in the reading room, and minimal light reflection from the monitors need to be considered when the workstations are positioned. Extraneous light in the reading room should be eliminated as much as possible while maintaining appropriate lighting for other necessary activities in the environment. It is also desirable to have large size monitors and an appropriate, adjustable viewing distance on the workstation. In addition, monitor flicker should be minimized and the noise level of the display monitor should be as low as possible. Finally, the interface design of the workstation has to be user-friendly and compliant with the conventional layout of functions and lists. In interface design, one has to consider the viewer's habits in viewing the images. Details such as continuous zooming have to be considered based on human perception study results. Icon design has to be intuitive, and icons have to be placed in conventional locations.

One should also know the circumstances that will reduce user performance so as to avoid them whenever possible. First of all, luminance levels of the display device that are too low decrease contrast sensitivity. On the other hand, a large increase in monitor luminance, beyond a certain level, may only generate a small improvement in contrast sensitivity at the expense of high cost. Also, the introduction of a nonuniform background (ie, luminance in the area around the target is not uniform) will make the target more difficult to be seen. The reduction in performance may partially be attributable to time lost searching in the nonuniform background.

Obviously, introduction of noise in the monitor will make the object detection more difficult, if not impossible. Lack of experience with the viewing environment, and lack of knowledge of the target shape and orientation will also decrease the performance.

Spatial displacement of target from the fixation point can make the target difficult to find. The visual acuity in the peripheral visual field is worse than at the fixation point. That is why it is important to have appropriate display field size so that the observer can scan the whole image in a short time. Then, one can focus on the regions of interest, and try to detect targets. A digital display system that is designed along these guidelines will find acceptance among users much faster than a display system that is not. Most commercial systems available today have not paid strict attention to these ergonomic details.

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APPENDIX 1

Suggested Quality Evaluation Checklist for Digital Display Systems

Monitor Luminance

1. What is the monitor luminance level?
2. Is an adequate luminance control provided? Is it easy to change?
3. What is the LUT? Is it appropriate and optimal for the type of application, for the type of exams? Is it customizable?
4. Do the high luminance levels in one part of the display area significantly degrade the contrast in the adjacent low luminance areas? (cross-over of the scan line or falloff distance?)
5. Is the illuminance spectral distribution optimal for best achromatic vision?
6. Do the characteristics of the monitor change with time? If so, how fast does it degrade?
7. What is the displayed dynamic range of monitor (I_{max}–I_{min})? Is it uniform over the entire screen?

Monitor Uniformity

1. Is the variation in luminance between the center and the edges of the display within the limits required by the intended use of the system?
2. Is there any nonuniform background on the monitors that will distract the viewer and decreases their performance?
3. Is there any noticeable flicker of the monitor?
4. Is the signal-to-noise ratio adequate of the monitor for low-contrast object observing?

Monitor Spatial Resolution

1. What is the number of scan lines per unit length, and width of the monitor?
2. What is the line spread function at both vertical and horizontal directions on the monitor?
3. Is the display field sufficiently large? Is the display field distorted and distracted?
4. Is the displayed image at the best viewing distance for the eye? Are the physical dimensions of the display and the operator compatible? Adjustable?
5. Is there difference in resolution between the center and the edges of the display within the limits of acceptance?
6. Is the raster line visible from the normal viewing distance?

Viewing Conditions

1. Are all sources of glare and veiling luminance eliminated or at least able to be shielded by the operator? Is there any antireflection coating on the monitor? Any antiglare devices?
2. Is the screen shielded from ambient illumination and reflections?
3. Is the screen tilted slightly? Is there an antireflective coating on the monitor?
4. Is the deflection angle of the CRT the minimum that can be used?
5. Are text displays (or secondary displays) adequately positioned? If not digital, is the luminance adequate? Is the luminance level close to the main monitors? (Otherwise the eyes may have to re-adapt to the different levels.)

User Interface Design

1. How many monitors can the system support?
2. Is the quality of the displayed image sufficient for the application? (eg, is the window and level and LUT modality optimized?)
3. Is the magnification range adequate? Is zooming continuous or discrete?
4. Is aberration excessive with the static image? Is the moving smooth and predictable (such as in cine mode)?
5. Is the speed of roaming and moving the images adequate (not jerky or delayed)?
6. Can the image be rotated as required? (3D image rotation smoothed? Any aliasing effects that may cause confusion from left to right?)
7. Are adequate scales provided to show control settings (such as window and level)?
8. Does the operation require minimal training, is it user-friendly and intuitive? Re-training costs (including off-duty time of technologists, radiologists?)

Workstation Design

1. Are all the control types (keyboard or console controls) appropriate and easy to use? Are the controls and displays in appropriate relation to each other?
2. Is monitor audio noise present and objectionable?
3. Is the viewing distance adjustable?
4. Can the monitor height be adjusted?

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