Enhanced Displays of Medical Images: Evaluation of the Effectiveness of Color, Motion, and Contour for Detecting and Localizing Liver Lesions

Steven E. Seltzer, MD[1], Patrick Cavanagh, PhD[2], Philip F. Judy, PhD[1], Richard G. Swensson, PhD[1], Larry Scarff, MS[3], Wayne Monsky, MS[4]

Rationale and Objectives. Many perceptual studies have shown that the detection of large, low-contrast targets is better either in color or in contrast-reversing presentations than in standard gray scale. We determined the value of several new display techniques for viewing liver computed tomography (CT) scans.

Methods. Eight observers (four radiologists and four nonradiologists) viewed sets of 100 liver CT images (50 with lesions and 50 without) under five display conditions on a Macintosh computer: (1) color (equiluminant color contrast); (2) color–luminance (combined luminance and chromatic contrast); (3) flicker (luminance contrast that reversed polarity at 2 Hz); (4) contour (shaded intensity mapping); and (5) control (conventional gray scale). Receiver operating characteristic (ROC) techniques were used for analysis.

Results. The measured ROC curve areas for the different viewing conditions were as follows: control = 0.77 ± 0.01 (mean ± standard error of the mean); color = 0.78 ± 0.01; color–luminance = 0.82 ± 0.01; flicker = 0.78 ± 0.01; and contour = 0.76 ± 0.01. The percentage of lesions correctly located ranged from 0.82 (color–luminance) to 0.75 (flicker). Performance under the color–luminance condition was significantly better than in the control condition ($p = .01$), whereas the other experimental conditions were not significantly different from the control condition ($p > .21$).

Conclusion. The use of mixed color and luminance displays may have perceptual advantages for radiologists and can improve performance over that of gray-scale viewing.

Key Words. Image enhancement; image display; computed tomography; image display and recording; liver computed tomography.

In the past two decades, there has been a dramatic increase in the clinical use of intrinsically digital imaging techniques. Computed tomography (CT) scanning and magnetic resonance (MR) imaging currently make up almost 30% of the total case volume of our department and represent an even higher proportion of all the images that are produced every day.

One of the well-accepted advantages of digital images is the potential to use advanced displays and computer graphics to enhance their perceptual impact and clinical utility. Despite the enormous potential for use of these

From the [1]Department of Radiology, Harvard Medical School, Brigham and Women's Hospital, Boston, MA; [2]Department of Psychology, Harvard University, Cambridge, MA; [3]Polaroid Medical Systems, Newton, MA; and [4]Georgetown University Medical Center, Washington, DC.

Address reprint requests to S. E. Seltzer, MD, Department of Radiology, Brigham and Women's Hospital, 75 Francis St., Boston, MA 02115.

Received January 10, 1995, and accepted for publication after revision April 25, 1995.

Acad Radiol 1995;2:748–755

computer-based tools, CRT-based viewing has been slow to win acceptance by radiologists [1], and the scientific assessment of the value of computerized enhancements to medical images has shown mixed results. For example, there has been little success in using color and other advanced display techniques for more fundamental applications such as detecting and localizing tumors [2]. Thus far, most of the successful uses of computer graphic enhancements, such as color and volume rendering, have been limited to "value-added" applications. By this, we mean the depiction of physiologic, anatomic, or pathologic information for specific purposes, such as the direction and velocity of flowing blood, myocardial excursion, tissue classification, surgical planning, three-dimensional visualization of normal and abnormal tissues, as well as merging of images across techniques [3–11].

Despite the limited success achieved thus far in the use of computer graphics methods to enhance radiologists' ability to perform basic perceptual tasks on digital images, there is evidence in the psychology and psychophysics literature that supports the usefulness of these methods. For example, Cavanagh [12] demonstrated that shapes can be depicted and recognized when defined by any of five different attributes: gray scale, color, texture, relative motion, and depth from binocular disparity. These attributes appear to correspond to discrete information-processing channels in the human visual system. Traditional gray-scale, film-based viewing systems stimulate only the luminance and texture systems. It could be argued that medical images displayed in a fashion that triggers the other channels instead of, or in addition to, the basic gray-scale channels might have greater perceptual salience than conventional display techniques.

Therefore, in the current study, we tested the hypothesis that medical image stimuli designed to activate the color, motion, and depth-processing channels would have perceptual advantages for radiologists performing basic clinical tasks. Specifically, we measured radiologists' ability to detect realistic but simulated lesions on liver CT scans under four experimental display conditions: equiluminant color, mixed color and luminance, flicker, and contour shaded; we also included a control condition (conventional gray scale).

MATERIALS AND METHODS

Study Design

Readers interpreted identical cases under each of the four experimental conditions and the control condition. In this way, each observer could serve as his or her own control. The order of presentation of the viewing conditions was balanced so that readers were equally likely to see each viewing condition in each position in the reading order.

Images

Fifty normal contrast-enhanced liver CT scans were harvested from routine clinical examinations on patients who had no clinical or imaging evidence of hepatic disease. The patients were scanned on a continuously rotating helical CT scanning system (Somatom Plus; Siemens Medical Systems, Iselin, NJ). The scanning parameters were as follows: 24- to 32-sec exposure, 120 kVp, 165–210 mA, 10-mm slice thickness, 1242 projections, and 180° linear interpretation reconstruction algorithm.

The images were transferred over an electronic network to a Macintosh computer-based workstation (Lite Box; Siemens Medical Systems), where they were saved as PICT files. Each image was then edited using Adobe Photoshop (Adobe Systems, Mountain View, CA), so that only the pixels containing the liver were retained and the remainder discarded. This procedure created image files of approximately 75 K, which we saved for use in the study.

The 50 normal liver CT scans served as backdrops onto which realistic but simulated liver tumors were placed. The lesions also were created using Adobe Photoshop and were circular low-density profiles, with edges blurred over 3 pixels to simulate the edge-response function of the CT scanner. The lesions were of five sizes ranging from 30 to 70 pixels in diameter, corresponding to 10–25 mm on the computer screen. Each lesion was represented at three levels of contrast (low, medium, and high) ranging from 3 to 16 pixel values below those of the adjacent liver. The precise combinations of lesion sizes and contrasts are presented in Table 1 and were chosen so that the five lesion sizes at each contrast level would have approximately the same Rose [13] signal-to-noise ratio (SNR) values. All lesions were darker than the liver.

TABLE 1: Lesion Characteristics

Size		Contrast (Digital Counts)		
Pixels	mm	High	Medium	Low
30	10	16	12	6
40	14	12	9	5
50	18	10	8	4
60	21	8	6	3
70	25	7	6	3

A location was chosen randomly within the liver for each lesion. This location had to satisfy the criterion that even the largest lesion would not overlap any normal structure or run past the liver's edge.

The lesions and backdrops were assembled into two sets of 100 stimuli (case sets A and B) for the study. Each set contained 50 "normal" stimuli that were composed only of the normal liver backdrops and 50 "abnormal" stimuli onto which lesions had been placed. Across all 200 stimuli, each location selected in the liver was viewed four times: normal (without a lesion) twice, low SNR once, medium, and high SNR once.

The images were presented on a 13-inch (33.02-cm) high-resolution RGB color monitor (Apple Computer, Cupertino, CA) that was controlled by a Macintosh computer (Apple Computer) and had 640 × 480 pixel spatial resolution, 256 intensity levels per color, and a 66-Hz noninterlaced raster. Internal look-up tables in the Macintosh were used to linearize the luminance output of each phosphor independently. Following calibration with a hand-held photometer (Minolta Chrome Meter II; Minolta Camera, Tokyo, Japan), the maximum luminances available from the red, green, and blue phosphors were 27.4, 59.0, and 5.2 cd/m^2, respectively. The phosphors of the monitor were determined by spectroradiometry to have CIE (Commission Internationale de l'Eclairage) x- and y-coordinates of 0.6084 and 0.3479 for red, 0.2490 and 0.6016 for green, and 0.1498 and 0.0519 for blue. The monitor white chromaticity was set to equal energy white, CIE x- and y-coordinates of 0.333 and 0.333. The stimuli covered 10.2 × 10.2 cm on the screen. The display had a mean luminance of 63.5 cd/m^2 in the gray-scale condition, 5.4 in the color condition, 12.8 in the mixed color–luminance condition, 25.6 in the reverse-polarity mode of the flicker condition, and 63.1 in the contour condition. A specialized program ran the display, controlled the user interface, and recorded observers' responses. For each condition, the center of the display window was set to be equivalent to 55 Hounsfield units (H), and the window width was 256 H; these are the clinically used "liver windows" in our department. We now discuss each of the display conditions.

Color. Equiluminant red and blue at the maximum available saturation were used to provide chromatic contrast between lesion and background. An equiluminant "balance" point was set for each observer [14]. The chromatic images were produced by modulating the red phosphor with the test image and modulating the blue phosphor with the test image in reverse contrast. These two images were superimposed on the monitor and their relative intensities adjusted so that the combined luminance was constant everywhere. The chromatic contrast in the image was defined in terms of the percentage of the maximum chrominance modulation obtainable with the phosphors involved.

Mixed color and luminance. Red and blue at 85% of the maximum available saturation provided a mixture of chromatic and luminance contrast between lesion and background. In the combined color and luminance image, the 85% color contrast red–blue image (red and blue modulated in opposite phase) was combined with a low-contrast, gray-scale image (all phosphors modulated in phase). In these mixed images, color and luminance were correlated in a fixed fashion (i.e., the image varied from dark blue through midgray to light red).

Flicker. Liver and lesion pixel values were alternated above and below the center pixel value at a rate of 2 Hz to produce a flickering effect. The presentation was otherwise conventional gray scale with only luminance contrast. Lesion and contrast-enhanced blood vessels were always of the opposite polarity.

Contour. The image was rendered as a gray-scale contour map with pixel values driving the apparent height of each pixel as well as its luminance. The rendering was performed by the shaded surface routine in the Interactive Data Language (IDL) software application (Research Systems, Boulder, CO) for the Macintosh. Images were viewed at an apparent angle of 80° from vertical, as if they were illuminated from a light source directly overhead. The lesions then appeared to be darker and lower than the surrounding liver. Contrast-carrying blood vessels appeared to be brighter and higher than the surrounding liver. For technical reasons, the lesions on the contour images had 50% more contrast than the lesions in the other conditions. If the lesions had less contrast, the readers could not discern any differences between the height of the lesion and the surrounding liver, and the intended perceptual effects could not be achieved. To allow a fair comparison between observer performance in the contour condition with that in the other display conditions, we reduced the measured contour performance proportionally (50%) to normalize it to the other conditions.

Gray scale. In this control condition, liver and lesion pixels were presented in a conventional format using 256 gray levels for luminance contrast only. The gray-scale images were produced by modulating all three phosphors in phase with the test image. An example of a typical stimulus image rendered in each of the display conditions is presented in Figure 1.

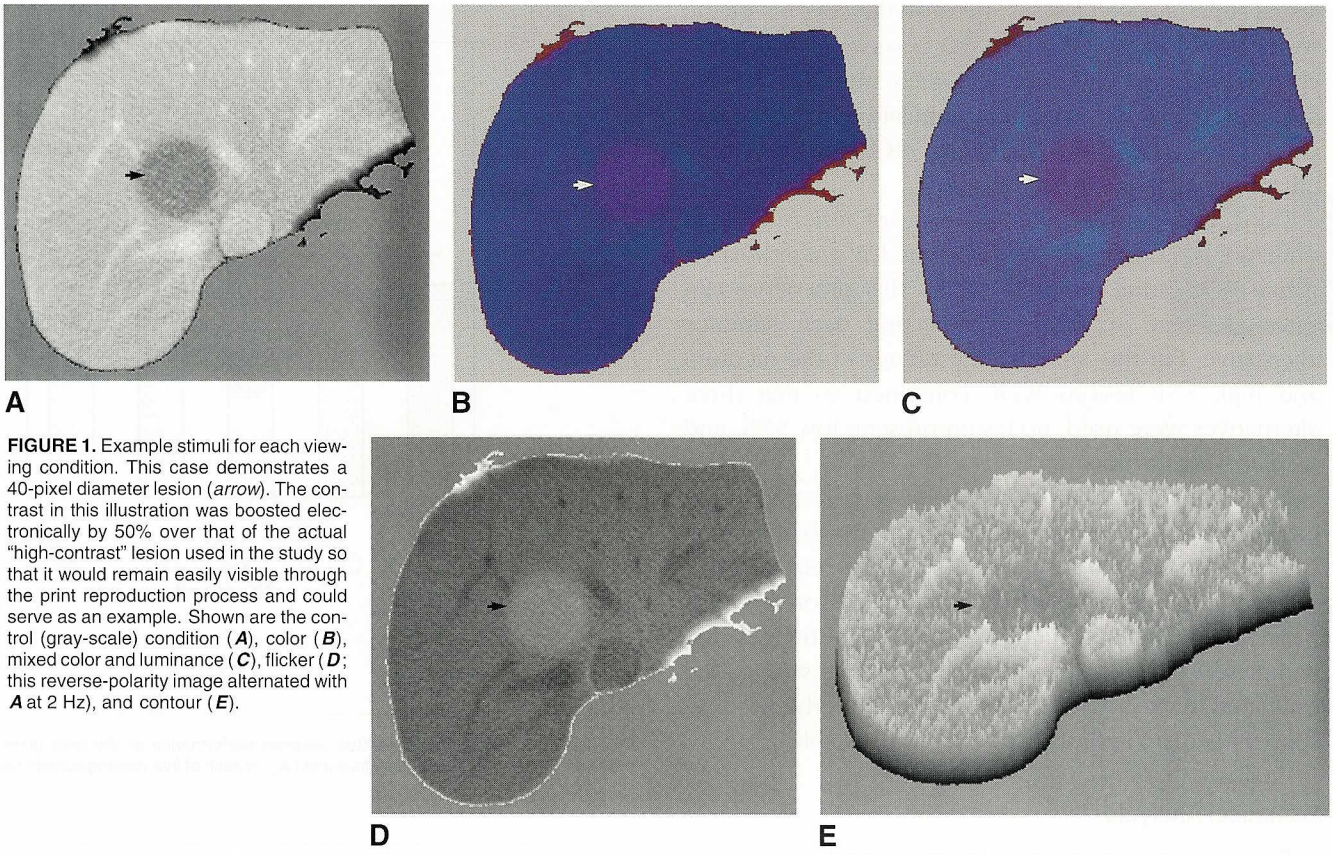

FIGURE 1. Example stimuli for each viewing condition. This case demonstrates a 40-pixel diameter lesion (*arrow*). The contrast in this illustration was boosted electronically by 50% over that of the actual "high-contrast" lesion used in the study so that it would remain easily visible through the print reproduction process and could serve as an example. Shown are the control (gray-scale) condition (***A***), color (***B***), mixed color and luminance (***C***), flicker (***D***; this reverse-polarity image alternated with ***A*** at 2 Hz), and contour (***E***).

Observers

Eight observers participated in the study: four radiologists and four nonradiologists who were experienced perceptual observers. Each observer was trained on the specifics of each experiment. Images were viewed in a darkened laboratory or office. Observers were given unlimited viewing time and could vary their viewing distance from 50 to 100 cm as well as their position, thus simulating the conditions in the clinical environment. The readers were informed about the spatial frequency response of the human visual system and were encouraged to vary their distance according to the range of lesion sizes encountered.

Observer Procedures

Observers were informed that each case set had a prior probability of .5 that a lesion would be present on a given image, but they were not informed about the lesion's location. They rated the likelihood that a lesion was present on a 5-category Likelihood scale that ranged from 1 (definitely absent) to 5 (definitely present). They indicated the lesion's most likely location on every stimulus image by pointing with a cursor.

Analysis of Observers' Readings

To analyze the observers' ability to detect lesions, we performed several types of analyses. First, the observers' ability to determine whether a lesion was present anywhere on the image was measured with receiver operating characteristic (ROC) curves. Each ROC curve was fitted by a maximum-likelihood procedure [15]. Their performance on this task was summarized by two key metrics: A_z is the area under the ROC curve and d_a is a monotonic index of the area beneath the curve. (These measures are limited because they do not take into account the correctness of the localization judgment; they summarize only the observer's ability to differentiate between images with and without lesions.)

Second, for each lesion image, the observers' ability to correctly determine the lesion's location was measured. For this second measurement, to allow for imprecision in the observers' localizations, a lesion was assumed to be correctly localized (CL) if the specified x- and y-coordinates were within the perimeter of the actual lesion. The observer's localization accuracy in a given condition was measured by p(CL), the fraction of the lesion-containing images on which their choices correctly localized the

actual superimposed lesions. Because the contour stimuli were viewed at an 80° angle, the observers' localization choices could not be scored accurately (the experimental software could not take this angulation into account when scoring the data). Therefore, p(CL) for these stimuli are not included in the results.

Third, to determine the influence of lesion SNR on observer performance, we performed a multiple-alternative ROC-fitting procedure [16]. This procedure can assess readers' accuracy in detecting each stimulus alternative. For this analysis, the ratings of the medium and high SNR lesions were combined so that three alternatives were used: no lesion present, low SNR, and medium–high SNR.

Interobserver variability was assessed by measuring the correlations among the ratings given to the same case read by two typical observers. A correlated ROC-fitting program (CORROC) [17] was used for this purpose. The CORROC fitting procedure estimates the parameters of two separate ROC curves as well as the estimated correlations between the underlying (presumed bivariate and normal) decision variables.

Statistical Analysis

To compare performance in the control (gray-scale) condition and each of the four experimental conditions for each observer, we used a Student's t test (paired two-tailed). A paired t test was used because each observer read each viewing condition and could therefore serve as his or her own control. Both detectability measures (A_z and d_a) as well as the fraction correctly localized were analyzed in this way. To assess the influence of the two data sets, between-reader variations, reader status (radiologist versus nonradiologist), and the order in which the conditions were read on observer performance, we conducted an analysis of variance. Statistical analyses were performed using the StatView (Abacus Concepts, Berkeley, CA) and JMP (SAS Institute, Cary, NC) software packages for the Macintosh.

RESULTS

Accuracy of Observers' Readings

The observers' ability to detect lesions on liver CT scans in the four experimental viewing conditions and the control condition is shown in Figure 2; their ability to locate lesions accurately is shown in Figure 3. Because the radiologists and nonradiologists performed equivalently in all conditions ($p \geq .10$), we pooled their results for the analyses.

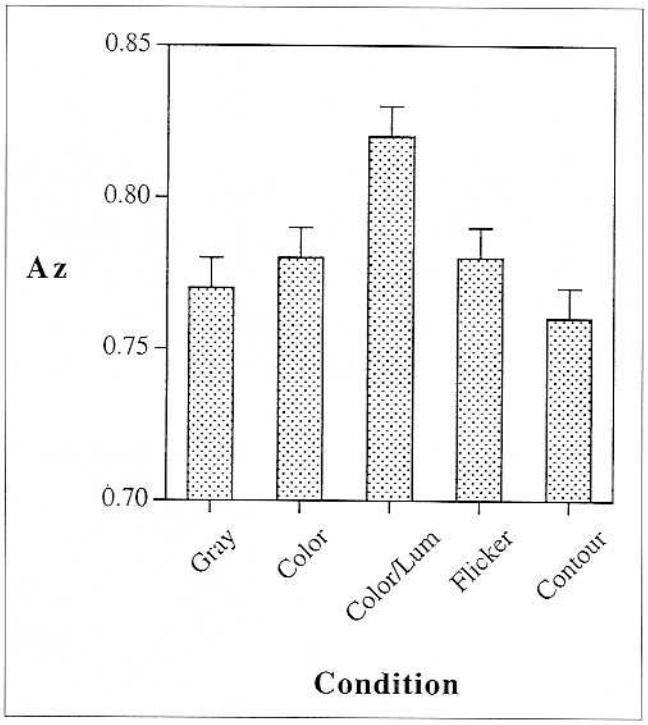

FIGURE 2. Histogram demonstrates observer performance as the area under the receiver operating characteristic curve (A_z) in each of five viewing conditions.

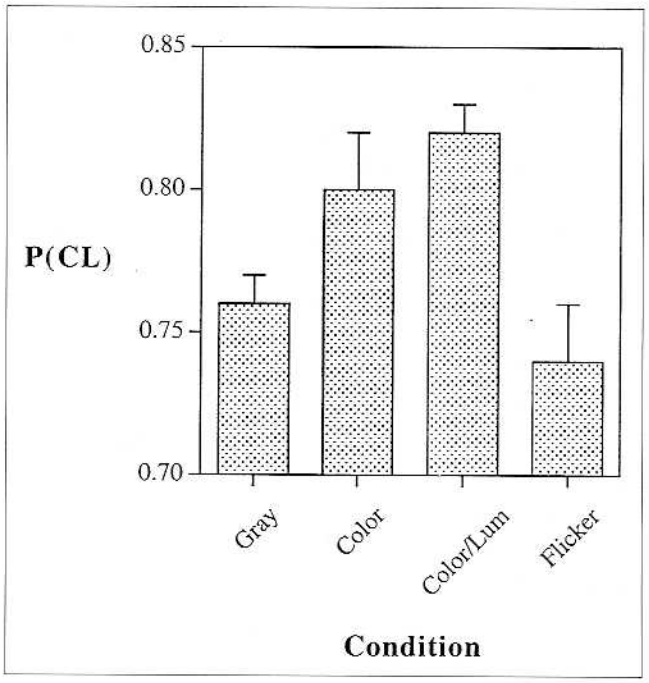

FIGURE 3. Histogram demonstrating the fraction of lesions correctly located in each of five viewing conditions. P(CL) = probability of a lesion being correctly localized.

Performance in the mixed color and luminance display condition ranked the best of all of the presentation modes and was significantly better than in the gray-scale

control condition (p = .01). Seven of eight observers performed better in the mixed color–luminance condition than in the control condition (Fig. 4). The A_z and d_a detectability indexes were 0.82 and 0.77, respectively, in the mixed color–luminance and gray-scale conditions (p = .01). The corresponding fractions of lesions correctly located were 0.82 and 0.76 (p = .002). Performance in the color-only condition ranked second best overall. However, performance in the color, flicker, and contour conditions was not significantly different from that in the control condition (p > .21 for detection accuracy; p > .08 for localization).

When the results were analyzed according to lesion stimulus strength, the findings were similar. Performance in the mixed color–luminance condition was superior to that in the control condition for both low and medium–high SNR lesions (p < .05). Performance in the color condition was significantly better than in the control condition only for the medium–high SNR lesions (p < .05). There were no other significant differences between the experimental conditions and the control condition. There also was no significant influence of case sets or viewing order on observers' performance (p > .09).

Observer Variability

Interobserver correlation coefficients ranged from .66 to .75 across the range of display conditions for the cases in which a lesion was present. As expected, the correlations were far lower for the cases in which no lesion was present, ranging from –.11 to .16. Between-reader variation was significant only in the gray-scale (p = .01) and mixed color–luminance (p = .03) viewing conditions, but not in any of the other conditions ($p \geq .21$).

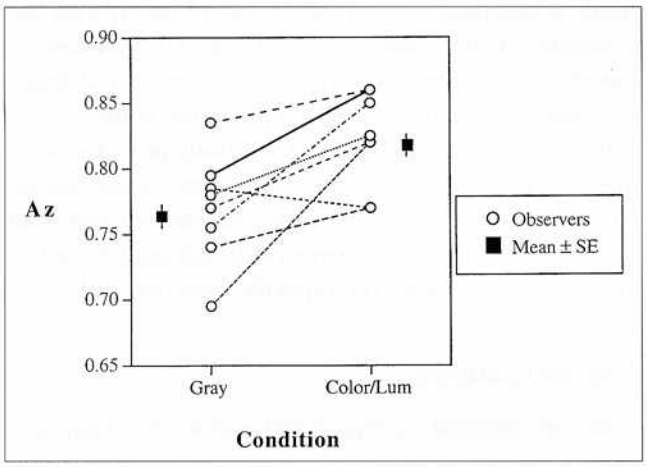

FIGURE 4. Performance of eight observers in the gray-scale and mixed color–luminance conditions. Az = area under the curve, SE = standard error of the mean, Lum = luminance.

DISCUSSION

The growing understanding of the functional organization of the human visual system suggests that computerized displays of medical images that go beyond use of static, gray-scale information could provide perceptual and diagnostic advantages. If a display activated a channel that was more powerful than the luminance channel or if it could activate constructively three or more of the visual system's information-processing channels, it could allow a radiologist to detect and locate more lesions than would be possible using a conventional display.

There is some evidence from other studies that this hypothesis is correct. Psychophysics research indicates that shapes determined by luminance, color, texture, motion, or depth vary widely in their visibility. In particular, although fine detail can be resolved only when it is defined by gray-scale information [18], large patterns are better detected when presented in color. In some cases, this advantage can be as much as 900% [19]. If one considers only gray-scale images, large features are also more easily detected if their contrast is repeatedly reversed (e.g., 2-Hz flicker) or if the feature is moved during viewing than when they are viewed at a constant contrast [20, 21]. These results from the psychophysical literature indicate clearly that these other attributes—color, motion, and flicker—may offer higher sensitivity for detecting large image features than does the standard gray-scale display. Interestingly, it has been demonstrated that observer efficiency is reduced for such larger lesions (<10 mm in diameter) on liver CT scans [22]. The implication is that color, motion, or flickering displays could prove especially helpful to radiologists.

There also is evidence in the medical domain for the value of activated additional perceptual attributes in improving lesion detection. Seltzer et al. [23] found that the addition of motion to gray-scale chest CT scan via a cine viewing system allowed radiologists to detect more lung nodules than they could when the same images were viewed conventionally on film transparencies.

Our results generally also support the hypothesis that displays that activate additional information-processing channels are helpful for medical imaging tasks. We found that the mixed color–luminance viewing condition, which would have been expected to activate three such channels (luminance, texture, and color), was

superior to a gray-scale display. However, the other experimental display conditions were not as successful—even though they activated additional channels—and were no better than the control condition. Therefore, these data suggest that not all types of multichannel displays will be successful.

The results achieved with innovative display methods used in this study may be conservative and could underestimate their true value for several reasons. First, particularly for the radiologist-observers in the study, there was a substantial discrepancy between their familiarity with gray-scale presentations and the experimental displays. The radiologists had tens of person-years' experience interpreting liver CT scans that were rendered in gray scale and presented on film, but the observers had only the experience of a training run of 100 cases with the novel displays. That extensive familiarity with gray-scale presentation could easily introduce a bias in favor of the control condition. Second, the experimental display conditions might not have been optimized. The specifics of each condition were selected on the basis of experience with them in nonmedical applications as well as limited data from pilot experiments. In addition, the luminance of the color-containing images was less than that of the gray-scale displays. A more detailed exploration of these experimental conditions with a focus on optimizing each of them was beyond the scope of our study.

None of the experimental displays tested in this study is likely to achieve acceptance in clinical practice in the short term. Radiologists have been reluctant to accept even CRT-based displays of gray-scale images [1], much less completely unfamiliar display techniques such as contour shading. In fact, in the current study, both the radiologists and nonradiologists alike found the color, flicker, and contour displays uncomfortable to look at. Only the gray-scale and mixed color–luminance displays were pleasing to view and visually comfortable. Another constraint on the use of these experimental displays is that the equipment required to render non–gray-scale displays is not readily available in a typical radiology department.

However, there are some reasons for cautious optimism about acceptance of advanced displays in the future. For example, radiologists already accept color displays in ultrasound and nuclear medicine, where color adds function information to the basic anatomic display. In future studies, researchers may develop additional scientific evidence that points to perceptual or diagnostic advantages of non–gray-scale displays. This evidence would provide a rational basis for their acceptance. The equipment required to produce such displays is becoming more readily available at low cost; even modern personal computers are capable of the task. Finally, advances in imaging technology are creating a climate in which computerized displays are gaining favor. Specifically, spiral CT scanning and fast MR imaging systems are capable of generating more than 100 images in a single examination. Conventional viewing methods (e.g., film hung on a multipanel alternator) are not well matched to the task of evaluating such large numbers of images. CRT-based methods are better able to display such data in a concise, salient fashion.

There are some limitations to our study. First, the experimental displays used were stylized to suit the particular capabilities of the Macintosh-based viewing environment that we used. They may not be easy to replicate on other systems. Second, the study was limited in scope: We did not extensively optimize the experimental display conditions, did not use image-processing schemes that could have improved lesion detection, made no attempt to compare CRT-based viewing conditions with film-based viewing, and did not mimic perfectly the clinical task of lesion detection. Observers were given substantial amounts of a priori information about the potential targets; they knew that only one lesion could be present as well as its expected polarity. Similarly, the lesions were not intended to reproduce perfectly actual liver tumors, that is, they were all round and uniformly dense and did not displace adjacent normal structures. Finally, although we found that the mixed color–luminance condition was the best with the particular stimuli used, we did not explore whether that result would hold over a larger range of lesion sizes and contrasts. A full exploration of the effectiveness of mixed color–luminance displays as a function of lesion contrast is an interesting subject for future study.

In conclusion, we believe that our study provides objective evidence that certain types of non–gray-scale displays have perceptual advantages over conventional gray-scale display methods. These perceptual advantages led to improved performance on a specific diagnostic task.

ACKNOWLEDGMENTS

We are grateful to Susan McLaughlin for help with manuscript preparation and to Raynald Comtois for the computer programming required to customize the experimental environment for the study.

REFERENCES

1. Coughlin BF, Seltzer SE, Judy PF, Swensson RG. Practices and attitudes about film-based and CRT-based interpretation. *J Digital Imaging* **1992**;5:50–53
2. Levkowitz H, Herman GT. Color scales for image data. *IEEE Comp Graph Applic* **1992**;12:72–80.
3. Vannier MW, Rickman D. Multispectral and color-aided displays. *Invest Radiol* **1989**;24:88–91.
4. Levkowitz H, Herman GT. Color in multidimensional multiparameter medical imaging. *Color Res Appl* **1986**;11:515–520.
5. Birnbaum BA, Noz ME, Chapnick J, et al. Hepatic hemagiomas: diagnosis with fusion of MR, CT and Tc-99m-labeled red blood cell SPECT images. *Radiology* **1991**;181:469–474.
6. Lavin DN, Pelizzari CA, Chen GTY, Chen C-T, Cooper MD. Retrospective geometric correlation of MR, CT and PET images. *Radiology* **1988**;169: 817–823.
7. Weiss KL, Stiring SO, Henderick EE, Cornhill JF, Chakeres DW. Hybrid color MR imaging displays. *AJR* **1987**;149:825–829.
8. Fishman EK, Drebin B, Magid D, et al. Volumetric rendering techniques: applications for three-dimensional imaging of the hip. *Radiology* **1987**; 163:737–738.
9. Fijioka M, Ohyama N, Honda T, et al. Holography of 3D surface reconstructed CT images. *J Comput Assist Tomogr* **1988**;12:175–178.
10. Fishman EK, Drebin RA, Hruban RH, Ney NR, Magid D. Three-dimensional reconstruction of the human body. *AJR* **1988**;150:1419–1420.
11. Hibbard LS, Glone JS, David DW, Hawkins RA. Three-dimensional representation and analysis of brain energy metabolism. *Science* **1987**;236: 1641–1646.
12. Cavanagh P. Reconstructing the third dimension: interactions between color, texture, motion, binocular disparity and shape. *Comp Vis Graph Image Proc* **1987**;37:171–195.
13. Rose A. The sensitivity performance of the human eye on an absolute scale. *J Opt Soc Am* **1948**;38:196–208.
14. Kaiser PK. Sensation luminance: a new name to distinguish CIE luminance from luminance dependent on an individual's spectral sensitivity. *Vis Res* **1988**;28:455–456.
15. Dorfman DD, Alf E. Maximum-likelihood estimation of parameters of signal-detection theory and determination of confidence interval-rating method data. *J Math Psych* **1969**;6:487–496.
16. Kijewski M. Swensson R, Judy P. Analysis of rating data from multiple-alternative tasks. *J Math Psych* **1989**;33:428–451.
17. Metz CE, Wang PL, Kronman HB. A new approach for testing the significance of differences between ROC curves measured from correlated data. In: Deconink F, ed. *Information processing in medical imaging*. The Hague, the Netherlands: Nijhoff, **1984**:432–435.
18. Reed MJ, Anstis SM. A chart demonstrating how Landolt acuity varies with contrast and retinal position. *Invest Ophthalmol Vis Sci* **1988**;29[suppl]:139.
19. Chaparro A, Stomeyer CF III, Huang EP, Kronaner RE, Eskew RT. Colour is what the eye sees best. *Nature* **1993**;361:348–350.
20. Kelly DH. Motion and vision: II. Stabilized spatiotemporal threshold surface. *J Opt Soc Am* 1979; 69:1340-1349.
21. Kelly DH. Spatiotemporal variation of chromatic and achromatic contrast thresholds. *J Opt Soc Am* **1983**;73:742–750.
22. Seltzer SE, Judy PF, Swensson RG, Chan KH, Nawfel RD. Flattening of the contrast-detail curve for large lesions on liver CT images. *Med Phys* **1994**;21:1547–1555.
23. Seltzer SE, Judy PF, Adams DF, et al. Cine display of spiral chest CT scans. *Radiology* **1994**;193(P):339.