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David V. Beard, R. Eugene Johnston
Osamu Toki, Claire Wilcox

Medical Image Display Group
Department of Computer Science
Department of Radiation Oncology
Department of Radiology
The University of North Carolina
Chapel Hill, NC 27599-3175

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David V. Beard, Ph.D.[1,2], R. Eugene Johnston, Ph.D.[1], Osamu Toki[2], and Claire Wilcox, M.D.[1]

[1] Department of Radiology
[2] Department of Computer Science
University of North Carolina, Chapel Hill.

Correspondence should be directed to:
David Beard
Department Of Radiology
CB# 7510 Old Clinic Bldg.
UNC-CH, School of Medicine
Chapel Hill, NC. 27599-7510
(919) 966-5467

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ABSTRACT

Understanding the visual scan patterns radiologists use to view medical images is critical to the design of image viewing devices. We used an Eyetracker, a device for recording eye and head movement, to determine the visual scan patterns during the interpretation of single and multiple computed tomographic (CT) scans presented on a four-over-four viewbox. CT scans were used because they represent complex viewing situations.

In two separate experiments, radiologists viewed patient folders containing single or multiple CT chest scans, and dictated a report. Eye movement was recorded with an eyetracker and video camera. After mounting the films in order, radiologists generally started with a sequential visual scan through the entire set of images, followed by careful examination of two to four clusters of one to four images, followed by dictating the interpretation report.

These results indicate that a well designed radiology workstation should provide an image index, arbitrarily and sequential movement through the image set, image comparison, and image marking.

Keywords: Human Factors, CT Interpretation, Radiology Workstations.

1. INTRODUCTION

Previous insight into the radiologist's interpretation process has been gained from experiments which recorded eye movements during image interpretation [Kundel 1969, Gale 1983, Rogers 1986, Beard 1987]. Much of this research focused on determining the source of interpretation errors. Experienced radiologists employ a variable, though basically, circumferential scan pattern when reading radiographs [Carmody 1980]. Visual scan patterns develop with experience [Kundel 1972], are affected by prior knowledge [Kundel 1969], and deviate from textbook recommendations [Gale 1983]. While some studies have suggested that misreadings (false negatives which range around 30% [Yerushallmy 1969, Smith 1967, Tuddenham 1962]) may occur because large areas of film are not viewed foveally [Llewellyn-Thomas 1969], or because there is non-uniform coverage of the film [Tuddenham 1961]. Eyetracking experiments indicate that only about 30% of missed lung nodules can be attributed to the lesion not having been foveally viewed [Kundel 1978]. More recently, studies have been initiated to determine workstation requirements for interpreting single small radiographs [Rogers 1989, Carbone 1989].

In 1986, the University of North Carolina developed a fingerpointing study to identify the visual visual scan patterns (fixation location and fixation duration) used by different radiologists when reading chest CT scans [Rogers 1986, Beard 1987]. In other words, how often, in what order, and how long was each image in a CT scan viewed? The accuracy level of fixation location was a single image (CT SLICE), not locations within the image. Five radiologists each read three CT scans using a four-over-four viewbox. Each CT scan was accompanied by its requisition form, and all its films could simultaneously fit onto the viewbox. The experimenter sat next to the radiologist and recorded times for certain activities, information accessed, placement of the films on the viewboxes, and the visual scan path as indicated by the radiologist. Radiologists were instructed to read and interpret a CT scan as naturally as possible, except to always point to the image under regard, and generate verbal descriptions.

Despite individual differences, basic similarities were observed among radiologists. Usually, they started a reading session by sequentially viewing the images while placing them on the viewboxes. In a second phase, radiologists concentrated (fixated) on several groups or clusters of specific images which were suspect. Finally, during a dictation (or reporting) phase, they scanned the images in a non-sequential manner fixating on those clusters of images on which they were reporting. These clusters were small. A cluster was operationally defined as a group of images which were connected by repeated fixation visual scan paths.

There were two possible sources of error in the fingerpointing approach: First, there was no information as to where the radiologist actually looked, only where he indicated he was looking. Second, the radiologist's visual scan path might have been somewhat modified by this task.

We repeated the fingerpointing study using an eyetracker, a device for measuring a subject's eye movement while performing a visual task. In this study, radiologists read patient folders containing both single and multiple CT scans. As with the fingerpointing study, our objectives were to determine the following: what visual scan patterns were used, how images in different CT scans are cross-compared, the size of clusters, how the films are managed on the viewbox space, and how much time is spent manipulating them.

We first describe the eyetracker study of single CT chest scans presenting the details of the study. A second eyetracker study is then described in which the radiologists interpret patient folders containing multiple CT scans. Finally, we briefly describe the implications this work has on the design of viable radiology workstations.

2. SINGLE CT CHEST SCANS

Patient folders containing single CT chest scans were chosen for the initial eyetracker study. CT chest scans are representative of the complex image manipulation and viewing tasks performed by radiologists.

2.1 Equipment and Observers

To determine eye and head movements as the radiologist conducted their reading of medical images, we used an eyetracking device, the Eye Mark Recorder Model V (EMR-V) manufactured by NAC, Inc (Figure 1). The system has two main components, the head/goggle unit, and the camera controller unit with remote control. The goggle unit is a head mounted unit that contains the eye-tracking optics and electronics. In operation an infrared LED light source (950 nm wavelength), which is not sensed by the eye projects a spot of light onto the subject's cornea. The spot is reflected from the cornea along an optical path, detected by a MOS image device (video camera), and sent to the camera controller for processing. Besides the MOS image devices for each eye there is a third "field unit" which observes the central portion of the subjects field of view. The camera controller provides power to the LED's and video cameras, and superimposes the eye position indicator spots onto the video image of the subject's field of view, which is in turn available to a video monitor and VCR. The unit's field of view is 60 degrees horizontal and 45 degrees vertical with an accuracy of 0.6 degrees.

PLACE FIGURE 1 HERE

Radiologists need to have freedom to move their heads and bodies in any fashion during the reading process. While many eyetrackers require fixed head position, the EMR-V allows such movement, and was chosen in order to minimize any intrusion on the radiologists' normal image reading process. The cost of allowing this freedom caused calibration to be more difficult and necessitated periodic calibration checks and occasional recalibration. This freedom of movement also compromised the eye-spot position accuracy. Horizontal eye-spot position accuracy was within 0.8 degrees, but in the vertical direction, as the eye moved toward the vertical limits, the accuracy degraded to about 3 degrees. Since a single CT image slice (15 images on a 14" by 17" sheet of film) is 3" by 4" at an average viewing distance of 20" we could resolve which image slice was being viewed, but not accurately which location within the image slice.

We taped each reading session with a video camera that recorded audio and time with a built-in stopwatch. These records helped in data analysis by providing timing information and voice clues as to what the radiologist was doing when.

We chose the four-over-four viewbox to simplify tracking which image was being viewed, and it typifies the standard display space available for viewing films. Four board certified radiologists and one senior radiology resident participated in the study. All subjects had experience with chest CT scans. None wore eyeglasses, but one had contact lenses. In our experience, contact lenses do not affect the use of the eyetracker. Each radiologist read an initial patient folder wearing the eyetracker to become comfortable with the device. All subjects reported that the eyetracker had not affected the quality of their interpretation or their operational methods, but that the eyetracker occasionally began to feel heavy toward the end of a reading session. The later occurred when the calibration procedure had been unusually long.

2.2 Procedure

The test material consisted of three different patient cases each having a single chest CT scan. Each CT scan contained about 30 to 40 image slices of which all image slices were recorded on film with an intensity window selected for viewing the mediastinum (three sheets of film). Another two sheets of film contained a subset of about 20 images that were recorded with an intensity window selected for viewing lung. The referring physician's requisition was provided. The radiologists were instructed to read the chest CT scans and report their interpretations using the same professional standards they would use in the clinic and end the study by replacing the films in the patient folder. Their report was dictated via a microphone onto the Eyetracker VCR. Informed consent was obtained after the procedure was explained.

2.3 Data Collection and Analysis

The objectives of this experimental work were to determine radiologists' film handling habits, inter-image search patterns, and how they used text information, CT planer views, and screen space. We also wanted to know the size and number of image clusters they viewed. A cluster was defined as the number of sequential images that were viewed together as a group. Cluster size is important in determining the minimum amount of display area a radiology workstation must have for simultaneous display of the smallest working group of images.

Visual scan patterns were determined manually. The tape was reviewed on a playback machine that allowed frame by frame viewing. From the video tapes, the experimenter documented the eye path of the subject noting when the radiologist paused (fixated) on an image. Repeated fixations on one or more images was defined as a cluster. We documented how many images were in a CT scan. We recorded the amount of time taken for each aspect of the reading session.

2.4 Results

2.4.1 Film Handling and Organization

Lung and Mediastinum (M) "intensity windowed" images were printed in two separate sequential series, and this separation was maintained by the radiologists when loading films onto the viewboxes. Generally, the radiologists placed M images on the bottom viewboxes, with the lung images either placed in a single pile on one upper viewbox, or spread out on the upper viewbox. One radiologist only used the bottom viewboxes, using the left three viewboxes for the M images, and piling the lung images on the right-most box. For the other radiologists, lung images on the upper viewboxes were viewed by looking up at them, by removing them and viewing them in hand, by "swapping" them with M images on the lower boxes, or by standing up.

Radiologists constantly changed their viewing position during the interpretation, often moving close to an image (zooming in) for a detailed look at the image, or moving away from the viewbox (zooming out) for a broader view. They would move left or right from the center to better view images on the outer viewboxes.

2.4.2 Visual Scan Patterns

The following visual scan pattern generally occurred during interpretation of these single CT scans: First, images were removed from the patient folder, sorted, and selected films were placed onto the viewbox. Images were often viewed as they were being loaded onto the viewboxes. Second, during what we call an overview phase, a systematic visual scan was performed over all the images. Sometimes this systematic search was by organ, but in general, a systematic sequential visual scan pattern was initially used to view the series of slices in the CT scan. In general, radiologists first viewed the images "intensity-windowed" for the mediastinum, followed by those "intensity windowed" for the lungs. Little or no cross comparison between images of different intensity windowing occurred. Third, during the detail phase, two to six critical clusters of image slices showing important radiology findings were reviewed. These clusters typically contained from one to four images, with occasionally as many as six, depending on the local anatomy and radiology finding under consideration. Radiologists averaged less than 0.2 seconds when moving eyes from one image to another, with typically two to five second pauses at each image. Fourth, during the dictation phase an interpretation report was generated, often while the images continued to be viewed. Fifth, the films were removed from the viewbox and replaced back into the patient folder.

A great deal of time was spent locating and non-sequentially accessing these small clusters of images showing important radiological findings. When asked how much of the patient's folder must be simultaneously viewed radiologists typically answer "all of it"[Rogers 1986, Beard 1987]. The above results contradict this, indicating a maximum of six images are viewed in rapid sequence demanding simultaneous display. But radiologists are not incorrect in feeling they need most of the patient folder displayed on the viewbox. The simultaneous display of the complete contents of a patient folder appeared to be used as a visual image index, allowing the radiologist to locate quickly any particular image, with rapid eye and head movement. This visual image index was not perfect. Some radiologists occasionally used their finger to mark the location of critical image clusters to speed subsequent access. The fingerpointing method could not show this because one hand was busy pointing out the eye's location, and the other manipulating films on the viewboxes.

2.4.3 Timing

Table 1 summarizes several categories of mean times for interpretations. Film Viewing/Dictation Time, is the total time radiologists spent actually viewing images, rather than moving films. Film Manipulation Time, is the total time radiologists spent moving and manipulating films, including time to load the images onto the viewboxes, and time for radiologists to move images from one location on the viewbox to another location. The time to unload the films and place them back into the patient's folders was not timed, but took about 10 seconds per case. Sometimes radiologists would hold images in their hands for viewing, making it difficult to separate image viewing time from film handling time. If a radiologist held a film to a light source, and his or her eyes moved over the images on the film, we considered it viewing time rather then film movement time. Total Interpretation time is from the moment radiologists picked up patient folders and started loading films until they replaced films into the folders. Sometimes partial times are missing due to eyetracker calibration loss.

Mean Times (min:sec) Case no.				
	#1	#2	#3	Mean
Film Manipulation*+	0:47	0:38	0:30	0:38
Film Viewing/Dictation	5:23	5:45	5:02	5:15
Total Interpretation	6:10	6:23	5:32	5:53

+ Some data points are missing due to eyetracker calibration loss.
* Does not include time to unload films from viewboxes.

Table 1
Mean Times for Single CT Scan Interpretation

3.0 MULTIPLE CT SCANS

3.1 Method

A second study was conducted with three patient folders each containing more than one CT scan with the number of films exceeding the available viewing space. The intent of this study was to document how radiologists used the available viewing area, how images from the different scans were compared with one another, and how the films were arranged and organized and the times taken to carry out the various steps in the reading process. The first patient folder contained two abdominal CT scans conducted two weeks apart. There were seven sheets of film with a total of 84 images. The second patient folder had three abdominal CT scans with a total of 12 sheets of film and 135 images. Finally, the third patient folder had three abdominal CT scans and one MR scan (obtained after the first CT scan) with a total of 18 sheets of film and 244 images. Radiologists were presented with the patient folder, the requisition for the most recent scan, and the radiologist report for the previous scan. The remainder of the experimental protocol remained the same as for the single CT scan. Informed consent was obtained after the procedure was explained.

Radiologists compared images from the various CT scans to evaluate changes that occurred over time. So, we observed the size of image clusters and how they were cross compared. The analysis of the video records, both from the video camera and the eyetracker, were manually reviewed, visual scan patterns were documented, and the number of fixations, image cluster size, and timing were obtained the same as for the single CT scan. Additional information was recorded as to how radiologists sorted and organized films on the viewbox and what they did with the films not occupying viewbox space.

3.2 Results

3.2.1 Film Handling and Organization

Radiologists began the interpretation by reading the requisition form, and in most cases the previous interpretation reports and then sorted through the various films to put them into an order of their liking. Images were usually quickly scanned during the sorting process. Images were piled by intensity window within a scan, with different piles for each scan . Piles were located either on the table or on the upper viewboxes. Radiologists appeared to use both the image appearance as well as the scan date printed on each image for sorting purposes.

In two cases, there were far more films than viewbox space, so radiologists kept the films in the piles, until needed. This resulted in a great deal of film movement during the interpretation, most likely, requiring a great deal of attention. Further, access to images in the piles was much slower than access to images displayed on the viewbox. Radiologists could no longer use their spatial knowledge of the viewbox organization to quickly index to the required image. Rather, they had to slowly move through a pile, looking at each film in turn until the desired one was located. The bottom panel (or row of four viewboxes) was generally used to hold the current CT scan, with the upper panel (and sometimes the outer viewboxes on the bottom panel used to hold films being compared. As with the single scan interpretation, films were read while being held, and the radiologists moved to the left and right, and sometimes stood up in order to better view the images. One radiologist organized each scan, along vertical rather than horizontal lines.

3.2.2 Visual Scan Patterns

After reading the requisition form, possibly the previous interpretation reports, and sorting the films, the radiologist began scanning the images. The initial overview phase observed with single CT scans was still evident, but more diverse. In different orders, all radiologists sequentially viewed the current scan, selectively viewed the previous scan (most likely focusing on radiologic findings identified by the requisition and previous interpretation report) and looked at any older images, (this varied with the radiologist and the case). This overview phase was again followed by a more complex detail phase with a focus on small clusters. A final dictation phase was again present with the same review of critical clusters. Radiologists repeatedly accessed related text information such as requisitions, interpretation reports, and text information such as scan step size written on the films, before and during the interpretation. This text information appeared to be very important to interpretation strategy for decision making.

One or more clusters from one scan were often compared, in pairs, with those from a previous scan to determine anatomical changes. Radiologists averaged less than 0.2 seconds when moving eyes from one image to another, with typically two to five second pauses at each image. Two methods of cluster comparison were observed. In one, the radiologists rapidly moved their eyes back and forth many times between two very small clusters with a maximum of a two second fixation per cluster. With the second method, somewhat larger clusters were compared with longer fixations on each cluster and far fewer movements back-and-forth. Radiologists averaged less than 0.2 seconds when moving eyes from one image to another, with typically two to five second pauses at each image. (Most cross comparisons occurred between the current and most recent previous scan). As before, clusters for single scan viewing typically ranged from one to four images with a maximum of six. However, when clusters from different scans were compared, they ranged from one to three images with a maximum of eight, for a total set of two to eight images normally requiring simultaneous display.

When comparing clusters, the films from the different scans were placed as close together as possible. Sometimes the films were placed above and below each other, sometimes side-by-side, and often one film remained on the viewbox with the other being hand-held close by.

3.2.3 Timing

Table two contains the times for manipulating the films and the total times for the interpretations. Blanks occurred in several sessions with case three due to the eyetracker loosing calibration. Both film manipulation time and total time were gathered. film viewing/dictation time was calculated and is the difference between the above two times. We show total time for individual radiologists reading individual cases to allow the reader to ascertain the degree of individual difference among radiologists as well as the time differences between cases. Radiologists # 5 and #6 were the residents.

As with most human factors studies, the differences among response times for individual radiologists is almost as much as that between the different cases. Film manipulation time increased with the number of films for a case. This observation matches what we have observed under clinical conditions and, we believe, reflects the additional amount of film sorting and searching a larger number of films entails. We feel this is because while scans older than the current and previous are always viewed, they are not examined in detail so that, after the first two CT scans, additional ones add only a small amount of viewing time. Note also that film viewing/dictation time does not change much between these three multiple scan cases, though viewing/dictation time is considerably more than this same time encountered for interpretations of single CT scans.

Mean Times (min:sec)				
	Case #1	Case #2	Case #3	Mean
Number of Films	7	13	18	
Rad. #1	6:50	10:59	10:55	9:35
Rad. #2	6:54	9:39	-	8:17
Rad. #3	12:36	16:23	-	14:30
Rad. #4	5:37	7:58	15:05	9:33
Rad. #5	8:20	12:33	-	8:20
Rad. #6	5:41	7:56	13:35	9:00
Total Interpretation	7:40	10:58	13:16	10:38
Film Manipulation	1:35	2:51	6:07	3:33
Film Viewing/Dictation	6:05	8:07	7:09	7:05
Film viewing/dictation = Total Time - Film manipulation				

Table 2
Times for Multiple CT Interpretation

4.0 DISCUSSION

The above results validate and expand upon the conclusions from the fingerpointing method described in the introduction. Radiologists sequentially overview the images, then examine critical clusters in detail, and finally dictate a report, again reviewing the clusters. While all the images arrayed on the viewbox appear to serve as a visual image index, typically only two to four small clusters consisting of from one to four images from the same scan are simultaneously viewed, and only clusters from different scans of from one to three images are pair-wise compared. The small cluster sizes, particularly in cross-comparison, may be related to the physical restraints of keeping the images close together when comparing them, or it may be due to attention/memory limitations.

The visual image index (all the images displayed on the viewbox) works well for image access, with radiologists generally moving their eyes directly to the target images (though they occasionally use their finger to mark a location for future reference). However, this visual image index fails when there are more films than viewbox space, as was often the case with multiple CT scans. There appears to be a great deal of manipulation of films for larger cases. Films must either be left in piles on nearby tables, or stacked on several viewboxes. A great deal of time may be wasted looking for particular films, removing and replacing films on the viewboxes.

We would expect somewhat improved film handling with an alternator, but it, by no means, solves the film handling problem. Our observation of radiologists using an alternator indicates two problems: first, radiologists sometimes loose track of the location of particular scans on the alternator's moving strip. Second, the "seek" time on the alternator, that is, the average time to locate a needed image or scan, can be quite long.

The fact that little comparison, as measured by the eyetracker records, was made between different intensity windowed images, such as those intensity windowed for lung versus bone, was a surprise to both the radiologists and the experimenters. The radiologists thought that they did physically make that comparison. In one of our previous experiments with a prototype electronic workstation [Johnston 1986] some radiologists did place the lung windowed image adjacent to the mediastinum windowed image and thought this was useful, but there was no indication that it was an important or necessary feature. Of course if that comparison can be conveniently and rapidly made with an electronic workstation, the radiologists habits may change. This qualification, of course, must be applied to all the results we obtained from studying the radiologist using the traditional display device that they have been trained on and which has imposed limitations on the reading process.

5.1 Implications for Radiology Workstation Design

Electronic workstations, are the essential means for physicians to view electronically stored medical images [Beard 1989, Pizer 1989]. However, producing an acceptable image-display radiology workstation is difficult. The typical viewbox array can easily display the equivalent of 32 high resolution display monitors (32 x 10242) which the physician can quickly access using techniques -- the movement of eyes and head -- that have been practiced for an entire professional career. Even the best workstations barely have this much real memory, let alone display space. Current workstations begin to show their advantage only with large patient folders that overflow viewboxes.

From our eyetracking research, we conclude that a viable radiology workstation for single and multiple CT scans at least needs the following: an image index for rapid access to patient folders, scans, and images; sequential and arbitrary viewing of images in a scan; access to all current patient text information; sufficient area to simultaneously display ten full-resolution CT images; function for comparing image clusters from different scans; function for marking critical images and clusters; and function for intensity windowing an image slice. Rapid response time, simple hand-motions, the ability to quickly measure anatomy, and an easy to understand interaction are also clearly needed.

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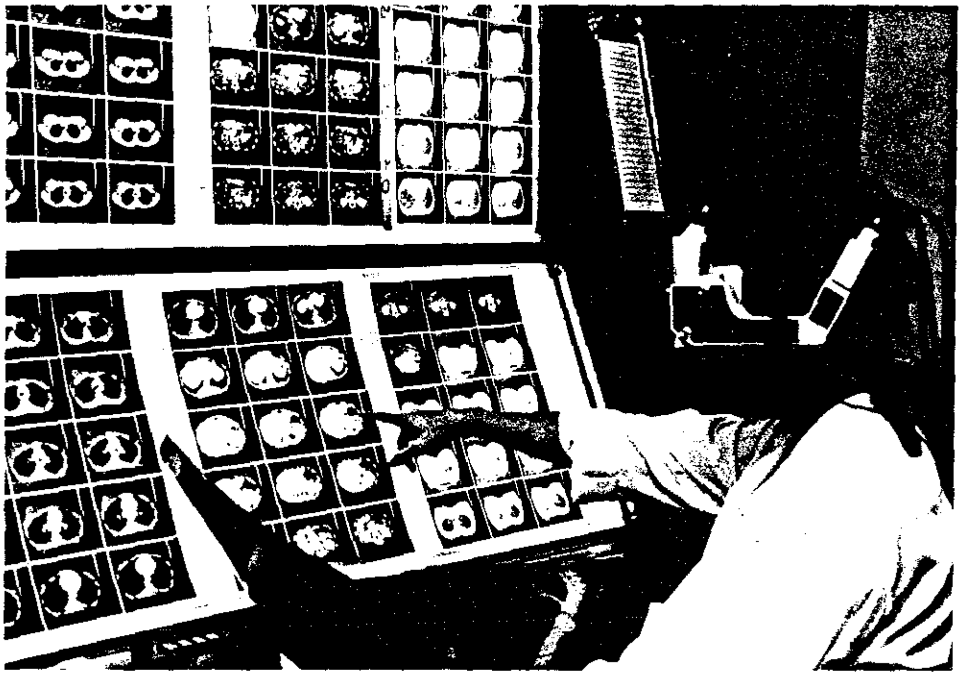

Figure 1
Interpreting a CT Scan with an Eyetracker