By Dr R Bertram, Dr J Kaakinen, Dr F Bensch, Dr L Helle, Dr E Lantto, Dr P Niemi & Dr N Lundbom

The potential of eye movement measures as a marker of expertise in interpreting CT studies

In this article, we present a summary of our recent study [1], in which we assessed eye movement behavior as a function of expertise during reading of abdominal computed tomography (CT) studies. We show that expertise in CT reading is characterized by enhanced perceptual processes and greater adaptivity in eye movement patterns in response to the demands of the task and environment. This could serve as indication of achieved competence during radiology resident training.

In medical fields such as pathology and radiology, residents train to develop visual pattern recognition skills towards an expert level. Several studies have shown that this development is reflected in changes in eye movement behavior. An increasing level of expertise is associated with faster times to first fixation on abnormalities [2], less coverage of images [3], longer saccades (i.e. rapid movements of the eye between fixation points) [4], and shorter overall viewing times [5]. These findings are accommodated by the global-focal model [6}, according to which experts concentrate on detailed inspection of the foveal area in parallel with global processing of the extrafoveal area (including the parafoveal area and the periphery). This entails that experts – upon viewing a radiograph – quickly extract the gist of the image in order to guide subsequent eye movements to suspicious locations. This quick extraction is related to superior encoding of domain-related configurations including visual patterns associated with normal and abnormal anatomic structures. Direct evidence for the quick extraction of extrafoveal information was provided by the flash view paradigm in which images are shown for a very short period of time. Even when images were shown for only 200 ms, experts performed well above chance level in identifying extrafoveal abnormalities in mammograms [7]. Under similarly brief exposure conditions, expert radiologists could detect chest nodules 15° away from the fixation point [8].

The studies reported above are all dedicated to understanding search in 2-D. Searching in volumetric space may lead to different search strategies and may require a different interpretation of eye movement measures. For instance, when reading chest CTs in the axial plane it may be needed to keep fixations within a relatively small area of interest in the x and y plane to distinguish a potential long nodule from a blood vessel, as they differ in how much they extend into the z-plane. This implies that relatively long saccades are taken as an indicator of visual expertise in the 2-D environment, are not necessarily a sign of increased visual expertise in a volumetric environment. Recent volumetric eye movement studies investigated global search strategies and found that performance and CT reading strategy differ between radiologists [9-12]. These studies allowed for free scrolling and were not specifically designed to investigate more detailed eye movement behavior and the development of perceptual skills in volumetric space. However, it is important to investigate this development, as image reading in volumetric space has become common practice in radiological assessments.

In our recent volumetric study [1] we aimed to gain insight into the development of perceptual processes and establish potential markers of visual expertise in eye movement patterns during interpretation of abdominal computed tomography studies presented at a fixed rate (3 and 5 frames per second (fps), respectively). Diagnostic performance and the eye movement behavior of early residents, advanced residents and specialists were assessed while they were to detect several lesions in the abdominal area across studies. Our paradigm can be seen as a "continuous

The Authors

Raymond Bertram, MSc, PhD[1]; **Johanna Kaakinen**, MSc, PhD[1]; **Frank Bensch**, MD, PhD[2]; **Laura Helle**, MSc, PhD[3]; **Eila Lantto**, MD, PhD[2]; **Pekka Niemi**, MD, PhD [4]; **Nina Lundbom**, MD, PhD[2]

1. Department of Psychology, University of Turku, Turku, Finland
2. Department of Diagnostic Radiology, HUS Medical Imaging Center, Helsinki University Central Hospital, University of Helsinki, Helsinki, Finland
3. Department of Teacher Education & Centre for Learning Research, University of Turku, Turku, Finland
4. Department of Radiology, Turku University Central Hospital, University of Turku, Turku, Finland

Corresponding author: Raymond Bertram

Tel: +358-3335063 Email: rayber@utu.fi

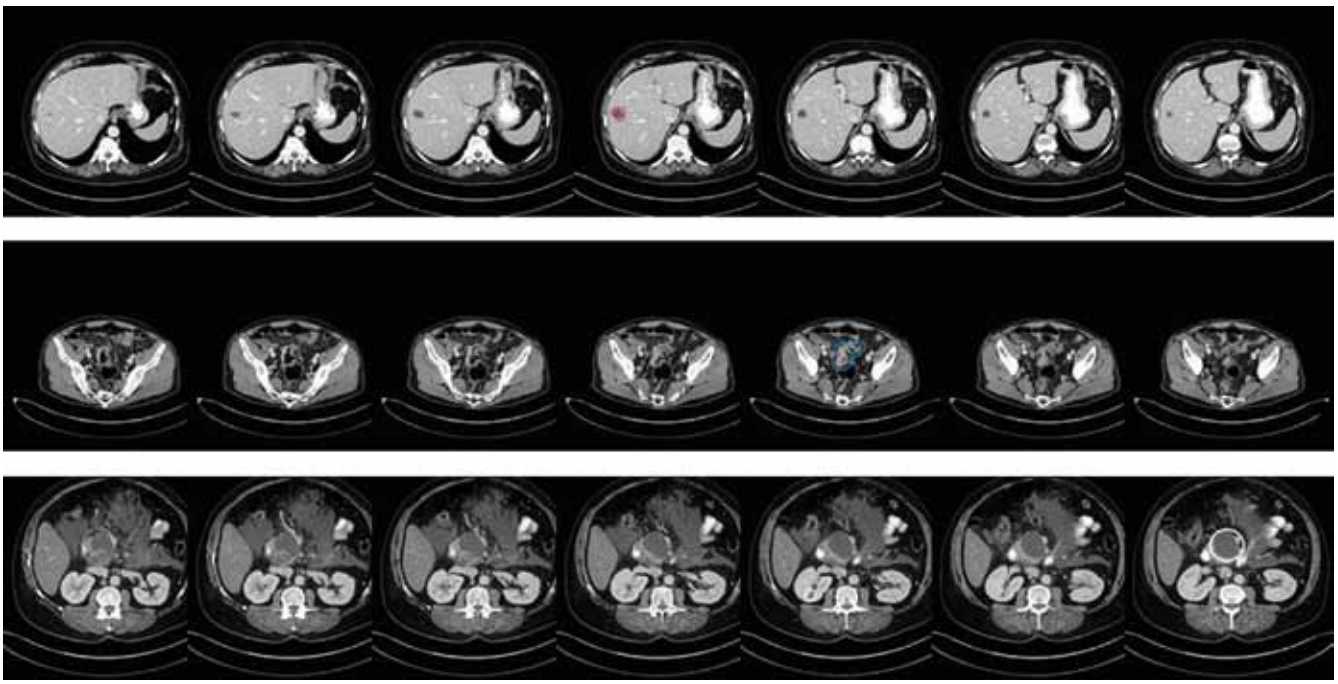

Figure 1. Upper panel. Liver cyst that was only visible for 7 sections. The lesion was not fixated directly by any of the participants, but detected by 90% nevertheless. Middle panel. Large bowel tumor, visually complex lesion that was visible on 10 sections only. Detected by 75% of the specialists, but by 25% of the residents only. Lower panel. Two lesions in the same timeframe: Dilation of pancreatic duct on section 1-7 and a kidney cyst on section 4-6. Attention has to be allocated to two lesions within the same timeframe

flash "view paradigm, as each image in the image stack was replaced with the next very swiftly. This deviates from a typical clinical setting, but has the advantage of absolute experimental control. Most importantly, it can be seen as an ultimate test of visual expertise for several reasons. First of all, lesions were at the moment of appearance mostly in the parafoveal region or periphery. This means that readers were required to not only inspect the foveal area, but also to use global vision to detect any potential abnormalities in the extrafoveal area [Figure 1]. Second, several lesions were present on only a few sections [Figure 1, upper panel] and consequently needed to be detected with extrafoveal vision only. Even when readers managed to foveally inspect these lesions, time to do so was very limited. Third, several lesions were not very salient and therefore hard to detect [Figure 1, middle panel]. Fourth, on several occasions more than one lesion appeared in the same sections forcing readers to allocate attention to different locations in the same timeframe (Figure 1, lower panel). These perceptual challenges call heavily on visual expertise and provide an opportunity to assess the extent to which domain-related configurations have developed and how they are served by efficient eye movement behavior.

DESIGN AND METHODOLOGY

Fifteen early and fourteen advanced residents as well as twelve specialists participated in the study. Hours at work on the same day before experimentation were registered for each participant and included in the analyses. Twenty-four experimental axial CT studies of the abdomen containing altogether 63 lesions and reformatted to 2.5-3 mm section thickness were selected and anonymized. The saliency of lesions was operationalized by number of sections the lesion was visible (from 2-98 sections, average 27). Also, contrast between the intensity of the lesions and their background was assessed. The CT studies contained 131-160 sections with half of the studies presented at 3 frames per second (fps) and the other at 5 fps (meaning that each section was visible for 333 ms and 200 ms, respectively). After presentation of each CT study, participants had to tick the appropriate findings on a paper checklist including 32 possible lesions covering most of the commonly encountered pathologies in the abdominal area. Eye movements were recorded by EyeLink 1000, which has a spatial resolution of 0.4 degrees.

RESULTS

Data were analyzed by generalized linear mixed effects models with separate analyses for Detection Rate (DR), Fixation Duration (FD) and Saccade Length (SL) as dependent variables. Independent variables were expertise group (early residents vs advanced residents vs specialists), lesion saliency (continuous variable), frame rate (3 vs 5 fps), presence of lesion (present or absent on section) and working hours before experimentation (continuous variable). DR of specialists was higher than that of residents with advanced residents detecting more lesions than early residents. For all groups, the DR was higher at 3 than at 5 fps, and the saliency of a lesion increased the likelihood of it being detected. An increased number of working hours decreased the lesion detection rate for early residents, but not for advanced residents or specialists. Early residents detected fewer of the low contrast abnormalities than specialists or advanced residents, whereas there were no differences between groups in the detection of high contrast abnormalities. A summary of the DR results is listed in Table 1.

The Fixation Duratiopns (FDs) of specialists and advanced residents increased when frame rate was increased from 3 to 5 fps, whereas there was no such an increase for early residents. Other manipulations elicited the same

Measure	Expertise group	Overall Rate	3 fps	5 fps	High contrast	Low contrast	Increased Saliency	Increase in working hours
DR (%)	Specialists	60	62	58	56	62	+	0
	Advanced residents	55	59	52	51	56	+	0
	Early residents	49	52	45	52	45	+	-

DR: Detection Rate; +: Increase in DR; 0: No change in DR; -: Decrease in DR

Table 1. Detection rate of lesions (in %) as a function of expertise, frame rate, contrast, saliency, and increased number of working hours before experimentation

reactions in all groups. Fixation durations were longer in the presence of a lesion in than when no lesion was present and in case of high-contrast lesions rather than low-contrast lesions.

Specialists shortened their Saccade Lenghts (SLs) more than residents in the presence of a lesion in comparison to whenever no lesion was present. In other respects all groups responded in the same manner to the manipulations. SL was shortened for high contrast in comparison to low contrast lesions and was lengthened — a frame rate of 5 fps in comparison to 3 fps.

Additional preliminary analyses on relatively salient and more obscure lesions indicated other interesting perceptual processes [13]. All expertise groups frequently visited or came close to the vicinity of the more obscure lesions; lesions that were more salient were fixated less, despite the fact that they were detected more often. Interestingly, when fixating lesions, specialists did so more quickly than residents.

DISCUSSION

This study showed both similarities and differences in detection performance and eye movement behavior in volumetric space as a function of expertise. The similarities underline that in this more complex environment (compared to a static 2D environment) residents are developing towards high-level domain-specific expertise in medical image reading. An earlier study by our research group [14] using a similar paradigm showed that — unlike residents - less experienced CT readers do not adapt fixation duration and saccade length to the appearance of abnormalities. Increasing fixation duration and shortening saccade length in a volumetric space paradigm is very sensible and allows for foveal scrutinization of a potential lesion in all planes. Both findings are thus indicative of growing visual expertise. Lesions were detected frequently in our continuous flash view paradigm, sometimes without even being fixated; this supports the idea that encoding of domain-related configurations has been established and that global vision is used to detect abnormal anatomic structures or to direct the eye towards suspicious regions. Nevertheless, detection rate is higher and the time to arrive at a lesion is shorter for specialists than advanced residents, who show better performance than early residents. This result pattern is evidence that the development of larger knowledge structures and the development of perceptual processes is gradual and that it requires a substantial amount of practice to reach the highest expertise level.

CONCLUSION

The current paradigm offers new possibilities for the assessment of the stage of development in resident training. In fact, a combination of the measures discussed in this paper can be used to create an eye movement profile of any resident and can be compared to expert behavior. Perhaps a more elaborate selection of CT studies and lesions would be needed to get a still more detailed picture of perceptual development. Also, it would be important to fully disentangle visual knowledge and perceptual abilities. A future study could for instance include a post-experimental session in which participants are given unlimited time and a free scrolling opportunity to determine what lesions are detected under unconstrained circumstances. However, the current set-up already provides ample evidence that also in volumetric space eye movement behavior is indicative of competence achieved during radiology resident training.

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