Mémoire de Maîtrise en médecine N°5528

Search of low contrast liver lesions in abdominal CT: an eye-tracking study in volumetric images

Marwa Shams
University of Lausanne, Switzerland

Alexandre Ba
Institute of Radiation Physics, University of Lausanne and Lausanne University Hospital, Switzerland

Sabine Schmidt
Lausanne University Hospital, Switzerland

Miguel P. Eckstein
University of California Santa Barbara, Department of Psychological and Brain Sciences, Santa Barbara, California 93106, USA

Francis R. Verdun
Institute of Radiation Physics, University of Lausanne and Lausanne University Hospital, Switzerland

François O. Bochud
Institute of Radiation Physics, University of Lausanne and Lausanne University Hospital, Switzerland

Lausanne, le 15 décembre 2018

Abstract

Eye-tracking studies can be particularly effective in improving tumor detection by radiologists. Several studies have attempted to characterize the ability of radiologists to search for and recognize different targets in various imaging modalities. However, few studies have associated eye-tracking experiments with scrolling volumetric images such as CT. Among them, a recent study on the reading of chest CT images showed that the detection strategies of radiologists could be classified in two categories, the "drillers" and the "scanners", according to an eye movement index (EMI), which quantifies the tendency of radiologists to perform large saccades in the investigated organ. However, the EMI doesn't take into account how radiologists scroll through the different volumetric data slices. We propose to add this information through the "number of courses", defined as the number of times a reader scrolls in a given direction during the analysis of the image. Our study aims to document this quantity and show how it could complement the EMI in order to quantify the strategy of the radiologist.

We considered a set of 15 asymptomatic liver CT images in which we inserted 1 to 5 metastases of two different contrast amplitudes. Twenty radiologists were asked to search for the metastases while their eye-gaze was followed by an eye-tracker.

The drillers are defined a going back and forth through the image stack, each time to exploring a different area in each image. We identified them as having a low EMI (e) and a large number of courses (C). The scanners are defined as scrolling coherently through the stack of images and exploring each image slice one after the other. They tend to have a high EMI (E) and a low number of courses (c). Interestingly, we observed that radiologists with a larger number of courses (eC and EC) tended to cover more volume in more time than radiologists with a lower number of courses (ec and ec). They found more metastasis and made less search errors than those with lower number of courses, especially when searching for lower contrast signals. Therefore, a driller defined by a low EMI and a high number of courses (eC) tend to be more efficient than scanners.

Our results show that for when the task becomes more difficult, the radiologists can improve their effectiveness by applying a strategy of a driller defined as an EMI and a higher number of courses. This could be used teaching resident radiologists.

1. Introduction

Colorectal cancer mortality in Europe reaches 190,000 patients per year and it is estimated that 50% of patients die due to hepatic metastases[1]. Hepatic metastases are already present when the cancer is diagnosed in 30 to 40% of cases [2] and the only known curative treatment is the resection of the primitive tumor and metastases [3]. As a consequence, a rapid and effective detection is essential to improve the vital prognosis [1].

Various volumetric imaging modalities can be employed to detect and characterize hepatic metastases: computed tomography (CT), positron emission tomography (PET) or magnetic resonance imaging (MRI)[4]. The most commonly employed imaging modality is helical CT. Its sensitivity depends on technical factors like image acquisition and reconstruction parameters, and also on the detected metastasis features like size and contrast[2]. In order to ensure an optimal metastases detection, the contrast between the hepatic tissue parenchyma and the metastases is maximized by using an intravenously injected contrast agent. During venous phase the latter appear as hypodense lesions surrounded by the contrast-enhanced homogeneous liver parenchyma. Thus, the sensitivity of detection reaches 80% on average[2]. However, how radiologists search through multi-slice CT can also have an impact on metastases detection and effectiveness, and strategies can substantially vary between radiologists[5], [6].

Image perception studies play an important role in understanding the radiologists' perceptual and cognitive processes of medical images. Characterizing how radiologists explore medical images can therefore help to improve hepatic metastases detection. For this purpose, eye-tracking studies have been used to gain insight on the radiologists ability to search and recognize various targets[5] in various imaging modalities[7]. However, few studies[7] have been reported to conduct eye-tracking experiments coupled with scrolling in volumetric images. A recent study on chest CT [6], showed that radiologists tend to follow two main reading strategies as they "scan" or "drill" through multi-slice CT images. According to this research, drillers focus on a small part of the organ while quickly scrolling images forward and backward, and scanners scan each level of the entire organ before moving to the next level and thus advance further slowly in depth. They found that drillers are more efficient in performing a visual search task as they find more lesions and cover more lung volume on average. The study categorized readers as drillers or scanners based on an eye movement index (EMI) that quantifies the tendency of radiologists to make large saccades. However, the EMI does not take into account how the readers scrolls through the different slices in the volumetric data. Another potentially important feature is the influence of signal characteristics on the readers' strategy. Although how search patterns vary with signal detectability has been examined with search in 2D displays [12], [13], [14], little is known about its influence on search with 3D volumetric data. Indeed, most of eye-tracking studies in volumetric images have focused on a single type of target without taking into account the possible influence of signal features (signal size, shape or contrast) on search effectiveness and strategies [5], [7].

The present study investigates how radiologists search for low contrasts targets in volumetric CT images of liver, and what is the impact of signal contrast on search strategy. Our first goal was to develop more comprehensive metrics of eye movement search patterns with 3D volumes. We developed a set of new metrics based on the number of scrolls between fixations and contend that they complement the previously proposed EMI index. Our second goal was to evaluate the effect of signal contrast on 3D search patterns. For this purpose, we designed an experiment that tracked the visual fixations and saccades in multiple CT slices, coupled with the measure of scrolling patterns of 20 radiologists with variable training experience. We instructed them to perform a free search task of lesions with two low contrast levels in order to estimate their diagnostic performance and to identify patterns that characterize search in volumetric images.

2. Materials and methods

2.1 Liver CT data

2.1.1 CT acquisition

Our retrospective collection of patient examinations was approved by the local ethical board. We included 15 anonymized contrast-enhanced abdominal CT examinations from our hospital's database. In all of them the liver parenchyma had been reported as normal, in particular without any focal pathology. The examinations were performed on a 64-detector row CT machine (Discovery 750HD, GE Healthcare; Milwaukee, WI, USA). We performed a routine abdominal acquisition according to our standard clinical protocol (120kV, 300-400 mA, table speed 55 mm rotation (0.6 s), pitch 1.275, axial slice thickness/reconstruction interval 2.5 mm/2 mm). CT images were reconstructed according to our routine default setting, including FBP and ASIR with 25% blending. We intravenously injected iodinated contrast medium (Accupaque®, Iohexol, 300mgI/ml, GE Healthcare, volume in milliliters = bodyweight + 30 ml) at a flow rate of 3ml/s. We used automatic tube current modulation in all 3 axes (SmartmA).

2.1.2 Cases preparation for reader study

Stimulus material used for the reader study was hybrid CT images generated by inserting synthetic low contrast volumetric signal mimicking hypo-dense focal liver lesion. The signal size was 8 mm, which subtended a 0.8 degree visual angle on the readers' eye for the experiment setting. The signal profiles in all directions were fitted to real liver lesion profiles. We used the alpha blending technique that removes anatomical structures from the volume of interest and replaces it with another obtained by blending a uniform region and the signal[8]. An experienced radiologist designated the locations in the liver parenchyma free of main structures (veins, arteries) for signal insertion. Two sets of 15 distinct cases were created by inserting one to five low contrast signals (average = 3) in each case. The first set contained a signal contrast of -50 Hounsfield units (HU). The second set contained a signal contrast of -30HU. There were no cases with no signals. The resulting sets of hybrid images were visually assessed by an experienced radiologist. Each case was composed of 100 consecutive slices containing the whole liver.

2.2 Reader study

To track and record the reader's gaze, an eye-tracking device (EyeLink Remote or EyeLink1000, SR Research Ltd., Mississauga, Ontario, Canada) was positioned below the image display and calibrated in order to maintain the average gaze error below 1°.

The participants were seated in front of a 22 in. (56 cm) screen suited for medical images display in a reading room with low illuminance (<50 lux). The participant's head position was fixed in order to improve accuracy in eye gaze measurements with forehead- and chin-rest mount. Before each reading session, a calibration procedure was applied to ensure a good eye-tracking accuracy. An additional eye-tracking drift check was performed between each trial. The cases were presented with a magnification factor of 2 with a window level of 50 HU and a width of 300 HU. Readers had no possibility to zoom or pan the images, neither to adjust the image contrast.

By using a mouse-wheel, the readers could freely scroll forward and backward through all the slices and were instructed to mark a lesion at its center with a mouse-click. Before the actual trials, they were shown examples of the signal to be searched, and they were informed that each case contained at least one lesion to localize. No time limitation was imposed to encourage a thorough evaluation of each case. In total, 20 readers took part in the experiment with reading expertise ranging from 1 to 17 years. In terms of demography, the reader group consisted of one undergraduate medical student, sixteen 1-5 year radiology residents, three 5-8 year clinical body imaging fellows and one radiologist with an experience of 17 years in abdominal CT imaging.

2.3 Data record and quantification

From the first scrolling wheel activation until the end of the trial, the eye gaze position in x, y (within slice coordinates) and z (slice number) was recorded at 60-Hz rate. The marker position was recorded when the readers localized a lesion.

From the raw gaze data and markers positions, we derived the following search summary measurements: localization hit rate, perceptual and search error rate, search duration, saccades amplitude, liver coverage and strategy quantification. An observer's marking was considered a localization hit when it fell into a disk centered on the lesion's center coordinate, whose radius was twice the radius of the lesion. A perceptual error corresponded to a missed lesion that was encompassed by a gaze cone of 2° centered on gaze coordinate during search. A search error corresponds to a missed lesion that was not encompassed by a gaze cone of 2°. The search duration started from the first eye gaze that fell onto the liver and ended when the reader decided to terminate the trial. The saccade amplitude was defined as the distance between two consecutive fixations, measured in degrees.

The coverage was defined by the liver volume encompassed by a gaze cone defined by a 5° disk centered on the gaze coordinate. Every point of the image that fell within the 5° gaze cone was considered as visible. We chose 5° in order to be consistent with the literature and the concept of the useful field of view [9]. For a -50HU signal contrast more than 70% of the detection saccades were within 5° and for a -30HU signal contrast more than 87% of the detection saccades were within 5°.

In order to classify the readers according to their strategy, we measured their eye movement index (EMI) [6]. This parameter was developed for lung nodules detection, and we extended it to focal liver lesions. EMI was derived from the summation of two components: (1) the saccadic amplitude, measured in degree, and (2) the time-averaged number of crossings over a line that delimits the left and right parts of the liver, measured in s^{-1} (Figure 1). Before doing the summation, both quantities were normalized to the maximum value relatively to the readers' population. According to [6], readers tend to adopt two different search strategies as explained previously: drillers go back and forth during the trial, and each time they tend to explore a different area of the image. This leads to a low value of EMI because the reader makes few saccades and few crossovers. The few eye-movements in the (x,y) plane is compensated by many back and forth scrolls across image slices (z). The scanners scroll coherently in one direction throughout the image stack and tend to explore each image slice one after the other. This gives the scanners a high EMI value.

Because the scanners also tend to perform fewer back and forth scrolling than the drillers, we decided to measure the number of courses, which we defined as the number of times a reader scrolled in a given direction during the test. For instance, a reader who scrolled through the image stack in one direction, then reversed through a couple of image slices and finally scrolled again in the original direction until the last slice would have performed three courses.

In order to evaluate the potential link between the EMI and the number of courses, we first computed the mean values of these parameters for each reader. We then labelled each reader as having either a high or a low EMI, and respectively a high or a low number of courses. The threshold between high and low categories was defined by the median value among all the readers. Therefore, a reader was labelled as a high EMI with capital letter "E" if his or her mean EMI was above the median value computed among all the readers. Conversely, a reader with a mean EMI lower than the median was labelled with lowercase "e". We did similarly with the number of courses: a reader with a mean number of courses higher than the median of all the readers was labelled with a capital "C", and a reader below the median was labelled with lowercase "c".

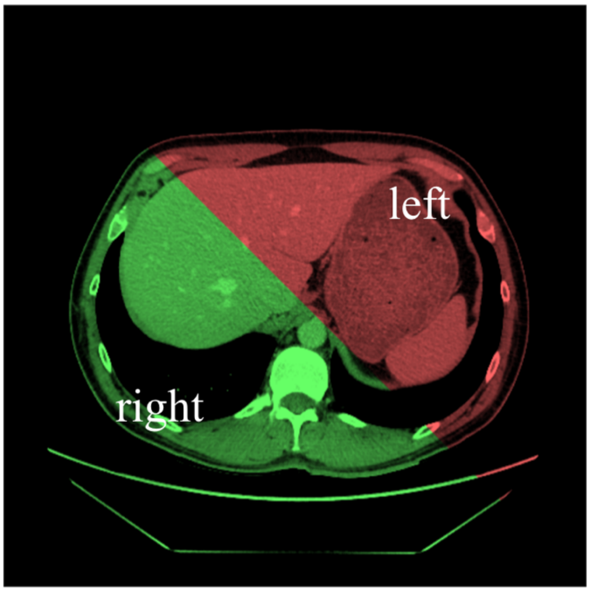

Figure 1. Example of one liver slice with colored overlay showing left and right parts of the liver in our study. On the anatomical level, the left and right liver are defined differently but we chose to separate it according to the left and right parts of the screen. This allows to have two almost similar volumes while anatomically the right liver represents the largest part of the organ. Having two same volumes is essential for the detection of crossovers because the number of crossover is defined as the number of times a saccade cross the line delimiting left and right liver during a trial. Furthermore, this separation facilitates the division of the organ on each test.

3. Results

3.1. Readers' strategy characterization

The number of courses was estimated by plotting the image slices (slice number in the z-direction) versus time for each trial and each reader. Figure 2 shows two archetypical examples: one with seven courses where we could suspect a drillers and one with a single course highly compatible with the behavior of a scanner, as described in [6].

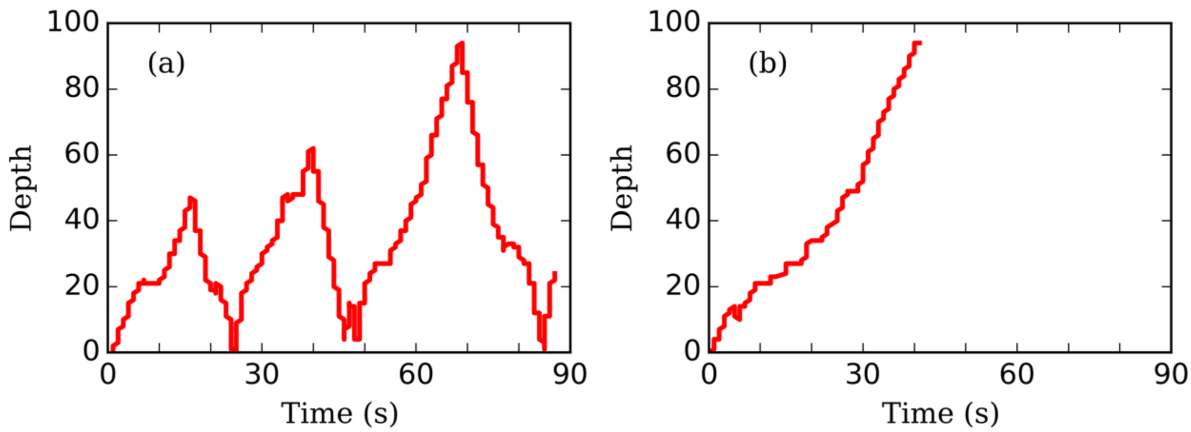

Figure 2. Depth (slice number in the z-direction) versus time plot example for typical a) driller and b) scanner. In this example, the number of courses per trial was 7 for the driller-like reader and 1 for the scanner-like reader.

Figure 3 shows the relationship between EMI and the mean number of courses for each reader. As described in the method section, this allowed us to distinguish four reader categories delimited by the medians of each parameter. The first group is identified as “Ec” for high EMI and low number of courses, the second group is “EC” for high EMI and high number of course, the third group is “ec” for low EMI and high low number of course, the fourth group is “eC” for low EMI and high number of course.

For the largest contrast (-50HU), the readers tend to be grouped in classes Ec and eC. For the lowest contrast (-30HU), this pattern is amplified.

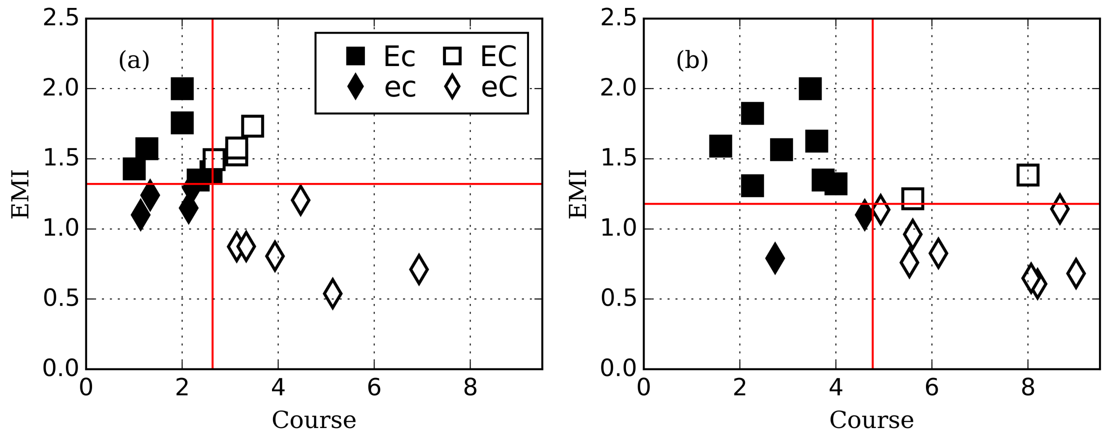

Figure 3. Eye movement index (EMI) versus the average number of courses over all trials for each contrast: a) – 50HU and b) – 30HU. Plain lines correspond to median value of EMI and number of courses population. Readers were grouped according to their EMI and number of courses in comparison to median values of the whole population.

Figure 4 presents the dependence of the two quantities that define the EMI: the mean crossover per second versus the mean saccadic amplitude. There is a positive correlation between these two quantities, with r = 0.82 (p< 0.01) and r = 0.92 (p< 0.01) for -50HU and -30HU respectively. In terms of number of courses, we observe that low values of EMI are associated with a high number of courses (white diamonds in the figure). Conversely, high values of EMI are associated with a low number of courses (black squares in the figure).

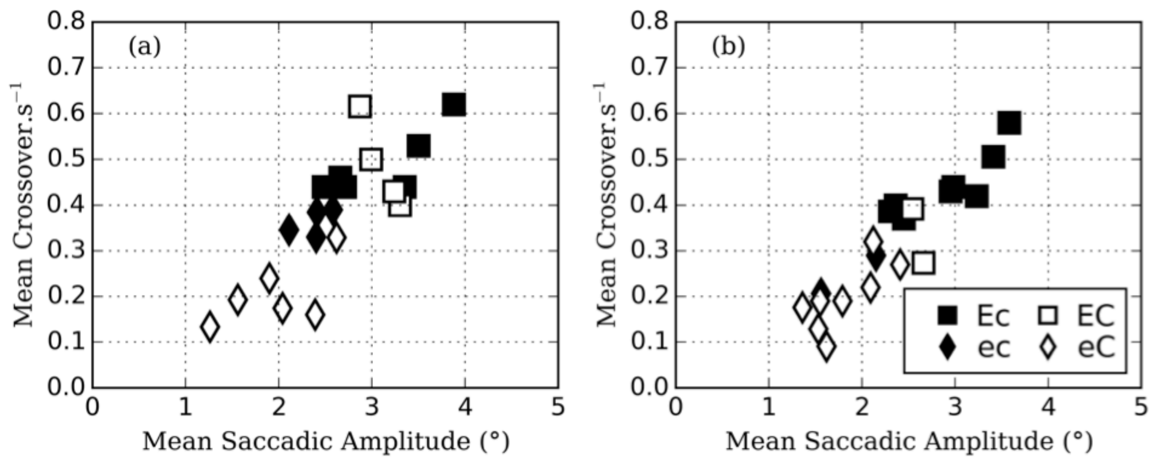

Figure 4. Relationship between the two parameters that define the EMI. Mean crossover per second versus mean saccadic amplitude for a) – 50HU and b) – 30HU.

3.2. Search performance

Figure 5 presents the liver volume coverage with respect to trial duration. Groups with high number of courses (eC and EC) tend to cover more volume (at -50HU (p=0.03) and at -30HU (p=0.01)) in more time (at -50HU (p<0.01) and at -30HU (p<0.01)) than groups with low number of courses (Ec and ec). The covered volume is positively correlated with trial duration for the high contrast (r = 0.65, p< 0.01), but not for the low-contrast signal (r = 0.41, p= 0.07). As expected, the decrease in signal contrast tends to increase the coverage (p<0.01) and the duration of trials (p<0.01). For one the participant we noticed a poor calibration accuracy leading to an underestimation of the covered volume. The participant data has been removed from the statistical analysis regarding covered volume.

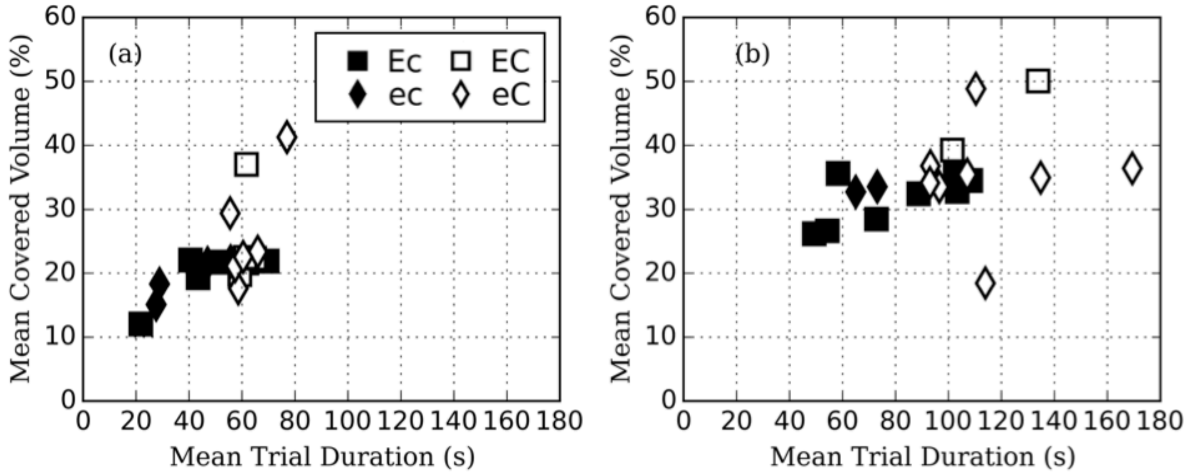

Figure 5. Liver volume coverage with respect to trial duration for a) – 50HU and b) – 30HU.

Figure 6 presents the localization hit rate with respect to the liver volume coverage. The groups with high number of courses (eC and EC) tend to show a higher covered volume than those with a low number of courses (ec and Ec). The hit rate at -50HU signal contrast is not different due to the lower difficulty of the task (p=0.23). However, the hit rate at - 30HU signal contrast is higher in groups with a higher number of courses (EC and EC) (p = 0.02).

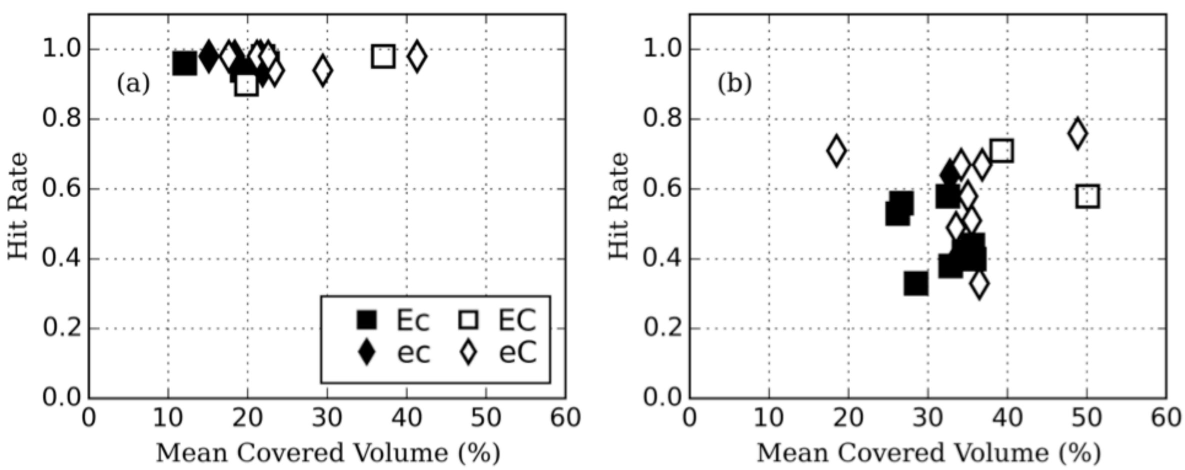

Figure 6. Liver volume coverage with respect to localization hit rate for a) – 50HU and b) – 30HU.

Figure 7 presents the search error rate versus the trial duration. As expected, the -50HU contrast images led to shorter observation times and significantly lower search errors than -30HU for all groups. For -30HU signal contrast, groups with high number of courses (eC and EC) tend to have longer trial duration and lower search error rates than groups with low number of courses (Ec and EC) ($p < 0.01$).

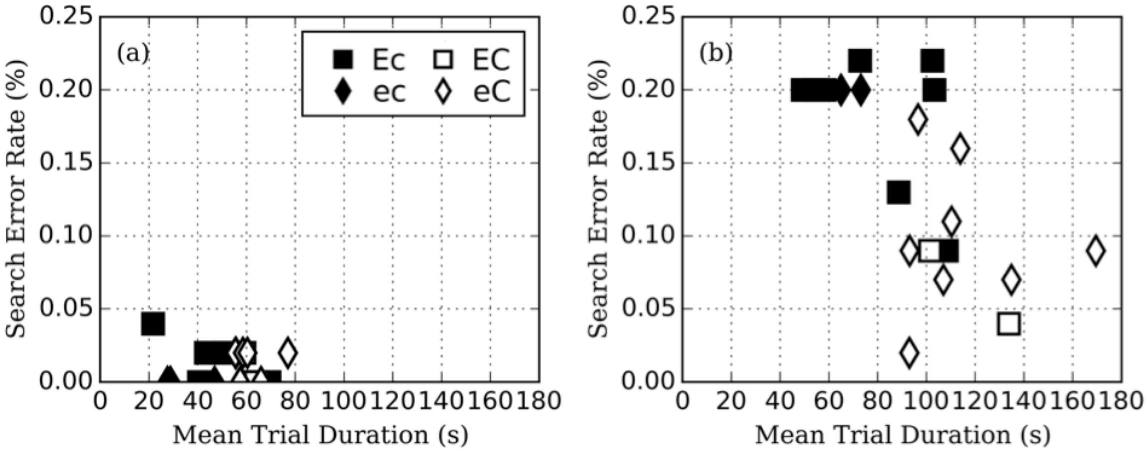

Figure 7. Search error rate versus trial duration for a) – 50HU and b) – 30HU.

Figure 8 presents the perceptual error rate versus the trial duration. The results show that the -50HU contrast images led to significantly fewer errors than -30HU contrast images ($p< 0.01$). The perceptual error rate does not appear to be dependent on the number of courses or the EMI.

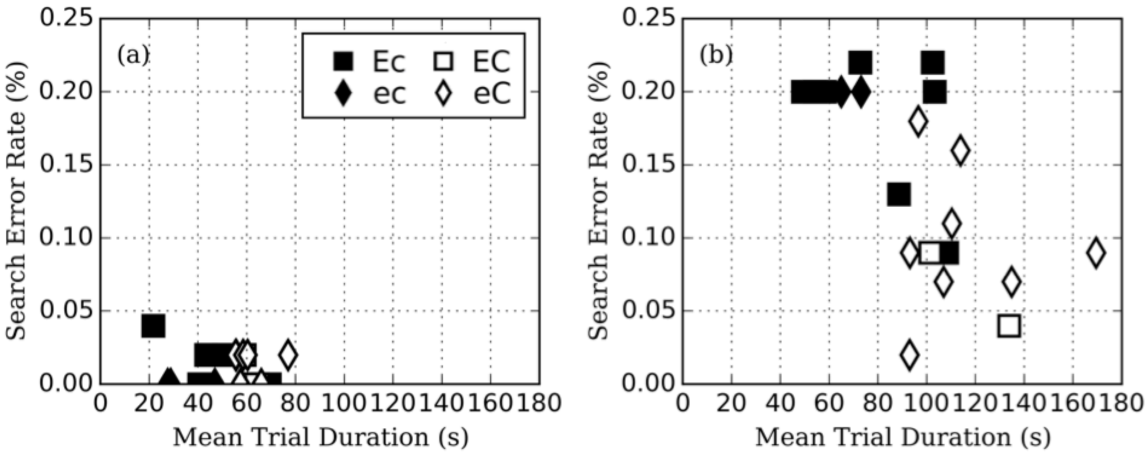

Figure 8. Perceptual error rate versus trial duration for a) – 50HU and b) – 30HU.

3.2. Effect of signal contrast on search strategy

To highlight the effect of a lower signal contrast on the search strategy, we estimated the difference in EMI and the mean number of courses when the signal contrast passes from -50HU to -30HU. In order to understand the variation of EMI, we also estimated the variation of its two components when the contrast is decreased: the saccadic amplitude and crossover per second. Figure 9 presents ΔEMI versus Δcourse and Δsaccadic amplitude versus Δcrossover per second for each reader, where Δ is the difference of the considered parameter from -50HU to -30HU. For all readers, Δcourse is positive, while for most readers, ΔEMI is negative. In other words, when the task becomes more difficult, the EMI tends to decrease and the number of courses increases. The fact that Δsaccadic amplitude and Δcrossover per second tend to be negative means that both parameters are involved in the decrease of EMI.

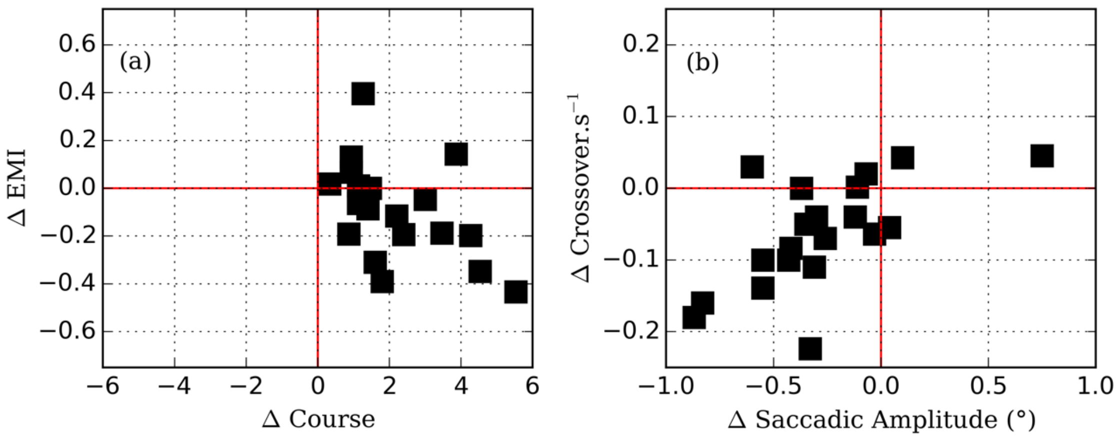

Figure 9. Effect of the signal contrast on EMI and number of courses (Δ is the difference of the considered parameter from -50HU to -30HU). a) ΔEMI versus Δcourse. b) Decomposition of the EMI in its two components: Δsaccadic amplitude versus Δcrossover per second.

4. Discussion

This study investigated the radiologists' visual search strategies in volumetric images and the influence of signal contrast. To define these strategies, we use two parameters EMI and the number of courses that allowed us to characterize two major categories of readers, drillers and scanners. As shown in Figure 3, EMI and the number of courses tend to capture similar properties of the readers' strategy with a low EMI associated to a high number of courses, and vice versa. But there is no bijective relationship between these two parameters and therefore, the classification of the readers according to their EMI only is not sufficient. One reason may be that there are probably more than two simple strategies. Depending on the difficulty of the task, the readers may adopt a strategy that is a composition of the driller/scanner dichotomy. Taking into account the number of courses to categorize the strategy clearly adds an essential feature in the context of 3D imaging, because the EMI only quantifies eye-movements in the x-y plane without taking into account the scrolling in the z-direction. Adding the number of courses therefore fills this void.

By taking into account the number of courses we were able to separate the data plotted in terms of volume coverage and trial duration, unlike the EMI. Another example is shown in Figure 7 and, where eC and EC readers are less prone to search and perceptual errors than ec and Ec readers. This latter result is in line with the results reported by Drew et al. [6] where the drillers' strategy (which is close to our definition of eC readers) was characterized as the most effective strategy in studies of volumetric chest images investigations. Therefore, we conclude that coupling the number of courses with the EMI may provide a more complete description of the visual search strategy in volumetric images. Furthermore, one disadvantage of the EMI measure is that it heavily relies on the eye-tracker accuracy and the somewhat arbitrary partitioning of the anatomy that defines the number of crossovers (anatomical triangles within the liver for the present paper).

Using EMI and the number of courses provides us with an explanation of how the strategy evolves when the task becomes more difficult. As shown in Figure 9a, lowering the signal contrast from -50HU to -30HU leads to a decrease of EMI and an increase of the number of courses. In other words, the readers become "more drillers" when the task is more difficult, with up to 5 additional courses and an EMI that loses up to 0.4 points. Figure 9b shows that this decrease of EMI corresponds both to shorter saccades (between 0 to 1° shorter) and to fewer crossovers (with a reduction of 0 to 1 crossover per 5 seconds), which is coherent with lower target detectability in the visual periphery for lower lesion contrast. In other words, the lower the visibility of the lesion in the periphery the lower the probability that the reader will direct a large saccade towards it.

Globally, our study also confirms what was already shown by Drew et al. [6]: drillers tend to be more effective than scanners. This is corroborated by a significant increase of covered volume for only a small additional time, which allows the reader to reduce the search errors, albeit not the perceptual ones.

We identified three main limitations to our study. The first one is that we used an identical gaze cone of 5 degrees for all readers. In reality, we expect this angle to vary between individual readers [10]. Furthermore, the signal detectability is known to vary continuously according to the eccentricity [11], and to jump from being detectable below 5° and invisible at higher eccentricity. However, we postulate that this should not affect the main observations of this work which averaged eye movement behavior across 20 observers. The second limitation is related to the demography of our subjects. With only three out of twenty radiologists with more than 5 years of professional experience in abdominal cross sectional imaging, it is possible that a part of their performance might be different from more experienced radiologists. The final limitation comes from the experiment paradigm itself. In clinical practice, radiologists are unlikely to fully explore each case as they did in this study, because in our experiment, the readers knew that each case had at least one lesion, which is not the case in practice. It is therefore possible that the driller strategy would not be as efficient in the real life.

5. Conclusions

Our study aims to propose a new icator, the number of courses, which makes it possible to complete the EMI, because these parameters taken together are able to refine the global categories of scanners and drillers. The analysis of the strategy in the case of a lower signal contrast shows that the readers tend to adapt to the higher difficulty by increasing their number of courses, while decreasing their eye saccade amplitude and the number of crossovers per second. In other words, confronted with a more difficult task, the radiologists improve their efficiency by behaving more like drillers than scanners.
Our findings could be used for radiologists involved in teaching activities. They may give the instruction that with low contrast signals, behaving like drillers is more efficient because it allows to increase the volume coverage with a small increase in time and therefore reduces the search error.

Acknowledgement

This work was supported by grant SNF 320030_156032/1 and National Institute of Health.

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