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ORIGINAL CONTRIBUTION

Cognitive load and processes during chest radiograph interpretation in the emergency department across the spectrum of expertise

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Abstract

Background: In the emergency department (ED), chest radiographs (CXRs) provide essential information for clinical diagnostic reasoning. Errors in interpretation by emergency physicians can lead to negative patient outcomes. To aid in teaching this important skill, an understanding of cognitive processes and cognitive load (CL) in CXR interpretation in emergency medicine (EM) personnel is warranted.

Methods: This study adopted a concurrent mixed-methods research design. Participant groups included medical students (M), junior (J) and senior (S) EM residents, and attending emergency physicians (P) in the ED at an academic hospital. To elucidate cognitive processes, a real-time cognitive task analysis during CXR interpretation was performed. Interviews were audio recorded, transcribed verbatim, and analyzed thematically. The interview was followed by a questionnaire, where participants rated their CL, stress, and confidence level.

Results: Levels of CL (M vs. S and M vs. P, $p = 0.002$; J vs. S, $p = 0.004$; J vs. P, $p = 0.005$) and stress (J vs. P, $p = 0.002$) decreased, while confidence levels increased (M vs. S, $p = 0.006$; J vs. S, $p \leq 0.001$; J vs. P, $p = 0.003$) as experience level increased. Qualitative analysis of interviews revealed four themes: checking behavior, information reduction, pattern recognition versus systematic viewing, and recognizing scope of practice. Experts commonly utilized checking behavior (e.g., comparison to prior radiographs) and deprioritized task irrelevant data. Experts used a general overview technique as their initial approach as opposed to a systematic viewing approach, and they more readily recognized an EM physicians' scope of practice in this task.

Conclusion: This study characterized differences in cognition that led to increased CL, stress, and lower level of confidence in EM learners during CXR interpretation and provided insight into expertise development in this important skill.

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INTRODUCTION

In the emergency department (ED), chest radiographs (CXRs) provide essential information to emergency medicine (EM) physicians and can guide clinical decisions.[1] It is important for EM physicians to be proficient in CXR interpretation to identify important pathologies and act upon the results, often before a radiologist can formally interpret the image.[2] CXR interpretation can be difficult,[3] and errors in the interpretation of CXRs can have negative consequences on patient care.[2] Previous studies have shown disagreement in CXR interpretation among emergency physicians as well as changes in patient management resulting from misinterpretation.[2,4] To mitigate these issues, effective training programs are necessary as well as an understanding of how CXR interpretation expertise is developed. Cognitive load (CL) and cognitive processes of the interpreter during the task are important factors to explore in this endeavor.

CL can be defined as a multidimensional construct representing the amount of working memory (WM) being used at a given time while performing a particular task and is a contributing factor in clinician performance in an acute medical setting.[5,6] WM has limited capacity compared to long-term memory. WM that is under- or overloaded has a significant impact on learning.[7] Cognitive load theory (CLT) is based on the design of instructional methods to optimize WM and CL during a task for efficient long-term memory encoding.[7] CLT focuses on WM management, and it is understood that when expertise is developed in a domain, information can be "chunked," thereby increasing the efficiency of WM.[8] Only a finite amount of information units can be present within the WM at a given time, but each of those units can contain multiple stimuli or subunits through chunking, thereby freeing up space for additional information in WM. Use of CLT can help elucidate what features of a task create a high CL load in novice learners and how experienced physicians manage their CL through strategies such as heuristics, cognitive schemas, or optimally chunking information for a given task.[7] In the context of this study, measuring CL allowed further understanding of expertise development of CXR interpretation as a core skill in EM.

CL during learning is divided into intrinsic (ICL), extraneous (ECL), and germane CL.[9] ICL refers to the complexity of a task and is dependent on the skill of the learner. ECL encompasses the CL imposed by suboptimal presentation of task information such as distractions, and germane CL refers to WM dedicated to processing intrinsic load, such as developing mental schemas.[9,10] The sum of these CL subtypes occupies the WM during a task, and because ICL is fixed for a particular learner performing a given task, CLT aims to reduce ECL, and to maximize germane load, giving the learner maximal resources to encode information to long term memory.[10] The load imposed by the task complexity and by a suboptimal learning environment should not exceed the WM capabilities of a specific learner; otherwise a state of cognitive overload ensues. There are various ways to measure CL including psychometric and physiologic methods.[5] One of the easiest methods is the Paas scale, a psychometric CL scale that has evidence for validity in this context and is thought to measure the sum of ICL and ECL on a scale of 1–9.[5]

CXR interpretation and viewing patterns have been extensively studied in the field of radiology,[2,4,11–14] but there is limited literature about this skill in EM. This is important because EM physicians have different environments, time constraints, and priorities compared to radiologists. Previous studies have shown that CXR interpretation performance among radiologists is correlated with level of experience.[2,11] Acute stress of EM physicians when on shift in the ED is a strong predictor of their CL.[8] In addition, previous EM research has found that the use of cognitive task analysis (CTA) to analyze how physicians think during resuscitations is useful and exposes important patterns of physician thought processes and elements of expertise.[15] CTA is a method that can be used to analyze cognitive processes during performance of a task or activity. CTA seeks to describe how people think and to understand cognition during a task and can be performed using interviews, self-reports, observation, or automated video capture.[16] In this study, we sought to combine analyses of CL and cognitive processes in practitioners along the EM expertise continuum during CXR interpretation on shift in the ED. In measuring the differences in CL and cognitive processes in EM personnel of varying levels of expertise, we hoped to gain insight into EM expertise in CXR interpretation in an authentic clinical setting.

METHODS

Study design and setting

This study adopted a concurrent mixed-methods research design,[17] consisting of a combination of quantitative questionnaire data and a qualitative CTA-based interview. CTA was utilized in the form of a "think-aloud" interview to understand the cognitive processes of expert physicians, residents, and novice medical students while they interpreted CXRs.

All data were collected in the ED at a Canadian tertiary care academic hospital. Interviews were conducted by a medical student research assistant (MM). Ethical approval was obtained through the university's research ethics board (file 6029972). To help maintain our methodologic rigor, the Consolidated Criteria for Reporting Qualitative Research checklist (COREQ)[18] guided our reporting (Data Supplement S1, Appendix S1, available as supporting information in the online version of this paper, which is available at http://onlinelibrary.wiley.com/doi/10.1002/aet2.10693/full).

Participants

Study participants were attending physicians, residents, and medical students. Participants were selected as a convenience sample, consisting of any EM personnel on shift at the times of data collection. Data were also collected at various times and over different ED shifts in an effort to capture different participants as well as add variability to the clinical presentations, as because some presentations requiring CXRs may be more likely to present on weekends or overnight for example.

Data collection

The research assistant approached participants immediately after a CXR was ordered in the ED, explained the study to them, obtained written informed consent for participation, and conducted the "think-aloud" interview when the participant was ready to view the radiograph for the first time. Once participants were ready, the research assistant began recording audio and prompted them to verbalize their thinking while they interpreted the CXR. A brief written questionnaire was administered following the interview, where participants graded their CL, task complexity, distractibility, stress level, and confidence related to their CXR interpretation. We used the Paas scale to measure total CL in participants, which asks participants to rate their CL from 1 to 9.[5] The case difficulty scale was utilized to measure perceived difficulty of the radiograph interpretation, because this is a hypothesized predictor of ICL.[19] The distraction scale was utilized as a predictor of participant ECL.[20] Stress levels were measured using the STAI-6 scale, which measures stress on a scale of 6–24, higher values representing higher levels of stress.[21] These four scales were adapted based on expert consensus from other psychometric questionnaires to make them relevant to our context and have been utilized in previous work by Vella et al.[8] to measure CL, ICL, ECL, and stress in emergency physicians while on shift in the ED. Interview guides and questionnaires are available in Appendix S1. All research encounters were deliberately short in duration as to minimally detract from a participant's typical approach and workflow; all encounters lasted 2 to 5 min in total. Each participant was interviewed only once. Interview questions were pilot tested by three third-year medical students prior to the start of data collection and modified to include of examples of "think-aloud" responses for clarification. This pilot process helped to ensure that the participants understood the prompting questions and were verbalizing their thought processes during the task.

Quantitative data analysis

Because the data violated assumptions of normality as determined by Shapiro-Wilk test, nonparametric Mann-Whitney U-tests were used to identify significant differences in questionnaire answers between participant groups (medical students, junior EM residents, senior EM residents, and attending emergency physicians). Statistical comparisons were made between each possible pair of participant groups for each discrete questionnaire question. A Bonferroni correction was utilized for p-value correction due to multiple comparisons of participant group data. Each questionnaire question entailed six comparisons; therefore, the original alpha level of 0.05 was adjusted to 0.008.

Qualitative data analysis

Audio recordings from the interviews did not contain any identifying patient information and were preliminarily transcribed using the Otter.ai transcription website (Los Altos, CA). Interview transcripts were then reviewed for transcription errors and corrected by the research assistant. Transcript files were then uploaded to NVivo (Version 12) qualitative software for analysis. The research assistant (MM) and a research associate (HB) coded one interview transcript together to develop a shared mindset and preliminary codebook. To assess intercoder reliability, they then coded four additional transcripts separately and compared their coding. The comparison resulted in a consensus-built codebook and any disagreements with codes were discussed until consensus was reached and adjustments to the coding were made to reflect their agreement. During this process, an intercoder reliability rating of 94% was achieved before discussions resulting in complete consensus. The five transcripts that were coded by two researchers were purposefully selected for diversity (across participant groups) and response complexity. The remaining transcripts were then coded during the data collection period by the research assistant to monitor for data saturation. More specifically, each transcript was coded individually with the smallest unit of analysis being the code, highlighting a specific sentence or part of the sentence. An inductive coding approach was utilized throughout the process,[22] and there were no predetermined codes prior to the coding process. After all transcripts were coded, the research assistant reorganized and consolidated codes where appropriate. Analysis was then conducted across transcripts to identify emerging themes across the participant groups. This was followed by grouping similar subthemes together under a broader theme. Qualitative interview data were continually reviewed during the data collection phase and thematic saturation was achieved when no new themes emerged from subsequent interviews. This process was iterative with names of codes and coding modified to better represent the data. The research assistant was also in regular contact with the research associate to discuss the coding process, possible biases, and initial interpretation. The research team then met to review the preliminary findings, where the principal investigator, coinvestigator, and research associate provided input regarding the chosen terminology, organization of the data, and data interpretation.

Research team and reflexivity

Project conception and trial design were performed by M.M., A.S., and A.H. M.M. is a male third-year medical student with interests in EM and medical education. A.S. and A.H. are male attending EM physicians with research backgrounds in medical education, simulation, and EM. Participant recruitment and data collection were conducted by M.M. Two of the 12 attending physician participants were known to M.M. in an academic capacity at the time of study. Qualitative open coding was primarily performed by M.M. after ensuring high intercoder reliability, with generation of new code and thematic development performed in collaboration with H.B., a female PhD-trained mixed-methods researcher with experience in similar CTA within EM research. Participant identity was not known by H.B.

Throughout the analysis process, M.M. and H.B. continually discussed the process of data collection and reflected on possible biases that may have been introduced at all stages of the research process. Part of these discussions focused on the conductance of interviews. This reflexive process aided MM in ensuring that minimal biases were introduced into subsequent interviews, such as how questions were posed and in what tone. For example, participants were prone to explain their interpretation to the research assistant in a didactic manner. We subsequently edited our prompt to explicitly ask participants to pretend as if the research assistant was not there. The emerging themes of the study and interpretation of the data were also continually reflected upon and shared with the whole research team to ensure the most accurate representation of the data.

RESULTS

Descriptive statistics

Junior residents were defined as EM PGY-1 to -2, and senior residents were defined as EM PGY-3 to -5. Overall, 39 participants were recruited for this study: 12 attending physicians (48 ± 2 years of age, four females and eight males), 11 senior residents (31 ± 2 years of age, two females and nine males), six junior residents (27 ± 2 years of age, five females and one male), and 10 medical students in their fourth year (25 ± 1 years of age, five females and five males). Two attending physicians declined to participate in the study and no participants declined in the remaining groups.

Quantitative findings

Questionnaire data are displayed as medians in Table 1 and revealed lower levels of CL and stress with increasing level of experience. Mann-Whitney U-tests indicated that CL was higher in medical students than senior residents (6 vs. 4, $U = 16.5$, $p = 0.002$) and attending physicians (6 vs. 4, $U = 17.5$, $p = 0.002$), and CL was higher in junior residents compared to senior residents (6 vs. 4, $U = 7.5$, $p = 0.004$) and attending physicians (6 vs. 4, $U = 9.5$, $p = 0.005$). Stress levels were higher in junior residents than attending physicians (10.5 vs. 7.5, $U = 6$, $p = 0.002$). Confidence level was lower in medical students compared to senior residents (0.7 vs. 0.9, $U = 20.5$, $p = 0.006$), junior residents compared to senior residents (0.6 vs. 0.9, $U = 2$, $p < 0.001$), and junior residents compared to attending physicians (0.6 vs. 0.9, $U = 8$, $p = 0.003$). Task complexity and distractions were not significantly different between groups, and all radiographs were interpreted correctly by participants based on retrospective comparison to the radiologist's final report. There were 39 CXRs interpreted in the study, 30 of which were deemed as having no significant pathology by a radiologist. This is representative of CXRs ordered in real EM settings, because most are normal and often utilized to rule out dangerous pathology.

Significant differences in questionnaire answers were not observed between medical students and junior residents as well as between senior residents and attending physicians. Therefore, in the following results and discussion, less experienced participants or novices will refer to medical students and junior residents, while more experienced participants will correspond to senior residents and attending physicians.

Qualitative findings

A total of four themes and 10 subthemes emerged from the qualitative data (Table 2). In the representative participant quotations below, *P* represents attending physician, *SR* represents senior resident, *JR* represents junior resident, and *MS* represents medical student followed by the participant number. Additional quotations organized by theme and subtheme are available in Appendix S3.

Theme 1: Checking behavior

Experienced participants more frequently compared the radiograph in question to a previous image when available. For example, participant P33 stated, "… just going to compare it to the old one. September. Pretty much the same." An additional checking behavior, seen frequently among all participant groups except medical students, was confirmation of the correct patient. Medical students were less likely to begin their interpretation with this confirmation, specifically patient name, medical ID, and date. For example, participant P36 stated, "what I would do is just make sure it's the right patient, the right date …" Overall, less experienced participants engaged in fewer checking behaviors.

TABLE 1 Postinterview questionnaire answers reported as participant group medians and interquartile range

Participant group	Mental effort (CL) (1–9)	Task complexity (ICL) (1–9)	Distractibility (ECL) (1–9)	Confidence level (0%–100%)	Stress level (6–24)
Medical students	6 (2)	5 (3)	7 (2)	70 (20)	9.5 (5)
Junior EM residents	6 (0)	5 (2)	6 (3)	60 (20)	10.5 (2)
Senior EM residents	4 (3)	3 (2)	7 (1)	90 (10)	8.0 (3)
Attending emergency physicians	4 (3)	3 (1)	7 (1)	90 (20)	7.5 (2)

Abbreviations: CL, cognitive load; ECL, extraneous cognitive load; ICL, intrinsic cognitive load.

TABLE 2 Summary of emergent themes and subthemes

Themes	Subthemes
1: Checking behavior	a. Comparison to previous radiograph b. Confirming proper image
2: Information reduction	a. Deprioritizing features based on clinical context b. Identification of less important information c. Discrete anatomical structures mentioned d. Ruling out pathologies e. Commenting on radiograph quality
3: Pattern recognition versus. Systematic viewing	a. General overview b. Systematic viewing
4: Recognizing scope of practice	a. Interpretation of an unremarkable radiograph for the purposes of EM decision making

Theme 2: Information reduction

Five attending physicians as well as one junior resident chose to actively deprioritize information in the CXR due to the clinical context of the patient because they were not concerned about certain pathologies. For example, participant P24 stated, "I was not concerned about the ribs, I'm not going to look at the ribs." In the majority of novices, a similar phenomenon was found, but instead information was not disregarded, and they identified clinically irrelevant information while still carefully considering all features of the radiograph. An example of this is seen in participant JR45's interview where they state, "I'm looking around bones … I don't see any sort of bony fractures. But I wouldn't expect it, not a traumatic story." Learners used the clinical context to identify the features of the CXR that they were expecting to be normal but continued viewing and considered all information regardless of the clinical context.

Information reduction was also seen in the verbalization of discrete anatomical structures as well as "rule-out" pathologies. Novices mentioned a higher number of anatomical structures during their interviews. For example, participant MS26 stated, "… you can see the ribs and you can see the clavicles, the mediastinum, you can see both diaphragms." Similarly, novices mentioned more rule-out pathologies during their interpretation; for example, as MS43 stated, "for volume overload, I'm looking for cardiomegaly, I'm looking for pleural effusions, I don't see any, I don't see any apical redistribution, and then for pneumonia, I don't see any areas of focal consolidation." More experienced participants mentioned fewer anatomical structures and rule-out pathologies, focusing more on "can't miss" pathologies.

Information reduction was further observed to be less common in novices, as they commented on the quality of the radiographs unlike more experienced participants. For example, participant MS14 stated, "… this looks like a pretty good X-ray for a portable. Especially with positioning." Learners more commonly mentioned the quality of the image, patient position, and image acquisition as part of their interpretation.

Theme 3: Pattern recognition versus systematic viewing

The theme of pattern recognition versus systematic viewing refers to the CXR interpretation technique. More experienced participants frequently started their interpretation with a general overview of the radiograph. For example, participant P2 stated, "So I just look at it in general first as I mentioned, just general gestalt if I see something that jumps out at me." In contrast, novices often verbalized a systematic approach to viewing the radiograph, such as an ABCDE approach.[23] For example, participant JR37 stated, "I'll use the standard approach that I was taught in med school, which is like an ABCDE thing. First, I'll start airway …". Overall systematic viewing as an initial approach was observed less in more experienced participants.

Theme 4: Recognizing scope of practice

The majority of radiographs interpreted in this study were unremarkable with no abnormal pathology. When asked to provide a diagnosis based on an unremarkable radiograph, more experienced participants more commonly responded with terms such as nil-acute, no acute changes, or no change from previous or they mentioned pathology they had ruled out. An example is seen in participant SR16's interview who stated "Not pneumonia" when asked to provide a diagnosis. When asked for a diagnosis based on the CXR they just interpreted, novices commonly labeled a radiograph as normal. In summary, more experienced participants focused on absence of radiographic changes that they were specifically looking for based on the clinical context.

DISCUSSION

This study demonstrates that differences exist in CL and cognitive processes of CXR interpretation along the spectrum of expertise in EM. Individuals with more EM experience were found to have lower CL and stress, higher level of confidence, more checking behavior, a superior ability to deprioritize task-irrelevant data, less systematic viewing, and a more appropriate recognition of scope of practice. The cognitive processes identified in this study provide insight into expertise in the task of CXR interpretation in the ED.

The finding of decreasing CL with increasing level of expertise is consistent with our current understanding of CL and expertise in medicine. Experts and novices think differently. Experts have information-rich cognitive schemas in their long-term memory and, as a result, can more easily bring additional information for processing into their WMs.[10] This, in turn, decreases their CL, because each individual unit or chunk of their WM contains more relevant information.[24,25] The noted decrease in levels of stress with increasing level of experience is also supported by previous work, which has shown that increasing experience correlates with decreasing levels of subjective stress in EM.[25] Additionally, confidence levels were lower among medical students and junior residents than senior residents and attendings. Low self-rated confidence levels in CXR interpretation in medical students and junior residents has been observed in previous studies[26,27] and may indicate the need for ongoing radiography teaching from medical school to early residency in addition to increasing clinical exposure to CXRs.

Checking behavior, the first qualitative emergent theme, was a phenomenon observed in more experienced participants. These participants more regularly checked for previously acquired radiographs and utilized a side-by-side comparison of new and previous radiographs when available. This finding is surprising because learners are less likely to discriminate small changes in CXRs due to the amount of task-irrelevant information[28] and would likely benefit more from viewing a comparison image. A key element to visual expertise is the ability to discriminate key features. By comparing radiographs to contrasting images, learners can better learn this skill by highlighting features that may be less conspicuous.[28] It is therefore likely that comparison to a previous image would decrease a learners CL and increase accuracy of interpretation. In addition, although a comparison image may initially be thought to increase the ICL of a task due to the need to process more information, it likely does the opposite, by removing elements of uncertainty with respect to certain questionable findings. For example, a normal CXR may contain subtle clinically insignificant findings that a learner can quickly ensure are normal for that particular patient by viewing a comparison image.

More experienced participants also displayed checking behavior by ensuring the proper radiograph, patient ID, and image acquisition date. This also may be further prompted by using a comparison image, because there are more images on the screen, which may make more experienced participants ensure that they are using the correct comparison as well as the appropriate primary image and may represent a well-developed routine that learners have not yet adopted. More experienced participants also likely better recognize the value of a comparison image when available due to past experiences.

Information reduction is a theory that predicts that experts in a task have a superior ability to distinguish task-relevant from task-irrelevant information, ultimately leading to lower levels of CL.[13] This phenomenon was observed through multiple subthemes in this study: deprioritizing features based on clinical context, quantity of anatomical structures, and rule-out pathologies mentioned as well as commenting on the quality of the CXR. Attending physicians actively identified task-irrelevant information during their interpretation and decided to proceed without addressing it, effectively removing it from their WM and decreasing ECL. Learners, on the other hand, were able to identify features that did not fit the clinical picture which likely increased the burden of ECL without this active deprioritization. Learners also verbalized more anatomical structures and more pathologies that they wanted to rule out and commented on the quality of the radiograph, likely increasing their WM load. These observations are largely in line with the information reduction hypothesis and may support the idea that mechanisms by which people discriminate between relevant and irrelevant information is under conscious, deliberate control.[29] The third theme of this study, pattern recognition versus systematic viewing, aligns with the dual process theory of reasoning that describes a system 1 versus a system 2 process. These are defined as general classes of cognitive processes, consisting of an intuitive or system 1 approach characterized by efficiency and automaticity and lower effort and is commonly reflexive and associated with higher skill. The analytical, or system 2, approach is characterized as slower, requiring higher awareness and effort, more deliberate, and less susceptible to bias.[30] More experienced participants commonly initiated their interpretation with a general overview or gestalt approach, congruent with a system 1 process. Novices displayed a more systematic approach or system 2 process. Current radiology teaching as well as textbooks advocate for the use of systematic viewing to ensure that a radiograph is scanned in full;[14] therefore, it makes sense that learners preferentially utilize this technique. Many of the more experienced participants in the study shifted to a more systematic approach after their initial general overview to ensure good visual coverage of an image, while learners were seldom observed to utilize a general overview first. This finding aligns with the concept that expertise in a task consists of a balance of system 1 and system 2 thinking.[31] Exclusively using a systematic approach may have contributed to higher levels of CL in medical students and junior residents in this study. The utility of teaching a systematic approach in isolation to learners is unproven because they might be unable to actively direct their attention as intended by this technique.[14] Previous research has shown that it may be beneficial to attempt teaching novices to think more like experts by integrating both intuitive and analytical teaching.[12,32] In practice this may include teaching learners how experts perform and how experts approach images. Although there may be some value in utilizing general scanning approaches, this must be balanced with core knowledge acquisition over a breadth of clinical cases given the specificity of expertise development.[33]

Finally, theme 4 describes the way in which EM personnel provide a diagnosis based on a CXR. When asked to provide a diagnosis based on an unremarkable CXR, attending physicians and senior residents frequently commented on the clinical context, stating that the image interpretation resulted in no changes to their management or no acute processes. Less experienced learners, on the other hand, commonly labeled images with specific diagnoses, like "normal." This has implications in understanding how learners think as well as how residents change their behavior as they become more skilled throughout their training. More experienced participants recognize the utility of a CXR in the ED and recognize the scope of their practice versus that of a radiologist who may have slightly different clinical goals (e.g., identifying all pulmonary nodules that require follow-up). Instead of labeling a CXR as "normal," they instead identify the presence or absence of any acute changes that would necessitate a change in clinical management in the short term. Previous research has found that it is likely that EM physicians are appropriately less thorough in interpretation of findings that they deem of secondary or tertiary significance.[34] This may explain why attending physicians less commonly labeled a CXR normal, because it is not in their scope of practice to completely clear pathology from a radiograph, but they instead dedicate their practice to ruling out dangerous pathology that will acutely harm their patient. Additionally, it is possible that approaching a radiograph with the goal of going so far as deeming it either "normal" or "abnormal" can pose greater ICL to a novice, as opposed to an emergency physician whose approach focuses on ruling out pathologies that will have a short-term impact.

The findings of this study have utility for informing EM radiology teaching and understanding expertise in CXR interpretation in the ED, by identifying what aspects of the task and individual approaches lead to increased CL. Checking behavior, deprioritizing task-irrelevant data, system 1 thinking as an initial approach, and recognition of an emergency physician's scope of practice in CXR interpretation were elements of expertise in this task. Practical implications from this work may include the emphasis of utilizing previous images for comparison when teaching medical students as well as verifying correct CXR image for a particular patient on a particular date. Additionally, learners may benefit from knowledge of the information reduction hypothesis as attempting to teach learners an approach that is more driven by the clinical context may decrease their CL and better direct their viewing behavior. Although analytical systematic approaches are important for novices to learn how to fully view a CXR, it is likely that learners can benefit from the addition of intuitive reasoning to their teaching once they have already developed the ability to analyze a radiograph in a systematic way. Finally, emergency physicians have different priorities than radiologists when viewing a CXR, and teaching programs may be more effective if they address this difference across specialties.

LIMITATIONS

This study has several limitations. Participant groups had small sample sizes. Although thematic saturation was achieved for qualitative analysis, quantitative analysis of small groups has limited statistical power.

All interviews took place in the same ED, although over the course of data collection, the environment greatly varied in terms of noise, crowdedness, the quantity of coworkers within earshot, or presence of a participant's educational seniors in the immediate area. Although participant stress and distractibility were recorded measures, medical students and residents may have modified their think-aloud protocol if they thought their superiors or coworkers could overhear the interview. Their stress levels may also have been falsely elevated because they were being recorded in the context of a research project. Additionally, distractibility in this study may have been suboptimally measured due to the study design. Participants were made aware of the study during their shift and had autonomy to participate in the interview at any time during the shift. This may have resulted in participants choosing interpret radiographs and participate when they had time to spare and had low stress levels.

This study was conducted at a single site, limiting the transferability of our findings because it is possible that the specific medical curriculum of the institution may affect radiograph interpretation and decrease the variability of the qualitative data.

Finally, the majority of the radiographs in this study were unremarkable (30/39), with no significant pathology. CXRs without pathology are still useful in elucidating cognitive processes of interpretation, because pathology is not always obvious, and careful evaluation is always required. Although mostly normal radiographs are a good representation of the real-world EM setting, this may limit the transferability of findings to abnormal CXRs.

CONCLUSION

This study demonstrated that differences exist in measured cognitive load and cognitive processes in chest radiograph interpretation along the spectrum of emergency medicine expertise. Higher levels of experience correlated with lower levels of cognitive load and stress and higher levels of confidence. More experienced participants exhibited more checking behavior, more information reduction strategies, and less systematic viewing of radiographs and had a greater appreciation for their scope of practice in chest radiograph interpretation. Knowledge of these cognitive processes has the potential to inform current and future radiograph interpretation teaching for medical learners in the ED.

CONFLICT OF INTEREST

The authors have no potential conflicts to disclose.

AUTHOR CONTRIBUTIONS

Michael Morra: study concept and design, acquisition of the data, analysis and interpretation of the data, drafting of the manuscript. Heather Braund: analysis and interpretation of the data, critical revision of the manuscript for important intellectual content. Andrew K. Hall: study concept and design, critical revision of the manuscript for important intellectual content, study supervision. Adam Szulewski: study concept and design, critical revision of the manuscript for important intellectual content, study supervision.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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