The Cognitive Basis for the Design of a Mammography Interpretation Tutor

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Abstract

The purpose of this paper is to present a cognitively-based and empirically-derived approach for the design of the RadTutor, a prototype computerized tutor to train radiology residents in diagnosing mammograms exhibiting breast diseases. A multitude of computer-based radiology training environments have recently been developed with the objective of supporting the acquisition of radiological expertise. In general, however, these systems have failed in several aspects including a failure to incorporate theoretical perspectives and empirical findings to the design of these systems. This paper outlines the conceptual framework for the development of the prototype which includes: (1) a discussion of the objectives and goals of the radiology residency training program, (2) a review and critique of existing computer-based radiology training environments, (3) a synthesis of an expert-novice study aimed at attaining a cognitive model of problem solving in mammogram interpretation (Azevedo, 1997), (4) a description of the results of analyses of authentic radiology resident teaching rounds, and (5) deriving instructional principles for the design of the mammography tutor.

Introduction

Radiological expertise is complex, involving several years of acquiring formalized medical knowledge as well as many years of clinical experience. It involves the integration of several distinct bodies of knowledge with separate organizing principles, including physiology, anatomy, pathophysiology, and projective geometry of radiography. Various theoretical frameworks postulate that the attainment of accurate visual diagnostic reasoning abilities involves the interaction of cognitive and perceptual factors.

This section outlines the cognitively-based and empirically-derived conceptual framework for the development of the RadTutor, a prototype computerized tutoring system to train residents to interpret mammograms. The conceptual framework incorporates the results of a recent cognitive study of mammogram interpretation (Azevedo, 1997) including the cognitive model of mammogram interpretation, the problem solving strategies used by staff radiologists and radiology residents, and the typical case-related errors. Furthermore, the framework is also based on: (1) an assessment of the state of cognitive science and learning in medicine, (1) a critical assessment of the haphazard nature of radiology residency training programs, (2) a review and critique of existing computer-based radiology training environments, (3) an analysis of authentic radiology resident teaching rounds, and (4) instructional principles for the design of the mammography tutor.

Residency Training Program in Radiology

The primary goal of the diagnostic radiology training program at McGill University is to produce well-rounded general radiologists who have been exposed to all aspects of subspecialty training (e.g., mammography) and have developed familiarity with all of the imaging techniques (e.g., MRI) and procedures. Becoming a well-rounded general radiologist necessitates a thorough knowledge of the relevant anatomy, physiology and pathology as well as the essentials of medicine and surgery. Radiation physics and biology must be well understood so that the principles can be applied to everyday practice.

Radiology residency programs have traditionally involved an apprenticeship experience, as have other medical education programs. This approach involves centering learning on the patient so that he/she becomes the focal point of all educational, training and research activities. The realistic constraints of the multitude of patients, variability of diseases/disorders, and the complexities of treatments and diagnoses leave little time for additional activities in a busy teaching hospital. The goal of the residency training program is to expose residents to a multitude of pertinent learning, training and research activities aimed at fostering the acquisition of radiological expertise. These activities include annual research days, conferences, formal lectures, and presentations with visiting professors, rounds and reporting sessions. Competence is developed and refined in instructional activities throughout the five-year residency training program. There is however several problems associated with the residency training program, which pose challenges for the design of a computer-based training environment.

In general, radiology residency training is somewhat haphazard. For example, teaching rounds vary in the (1) material taught, (2) quality of presentation by individual radiology staff members, (3) participation of residents during each session, (4) quantity of training experiences, (5) quality of training experiences, and (6) time that staff radiologists have at their disposal for preparing to teach in rounds and lectures. Lastly, the instructional objectives delineated in the residents training manual are too general and thus hamper any attempts at a formalized training program and also limit the objective assessment of residents' skills. For example, one of the objectives for a 4th year radiology resident is to "*have achieved diagnostic and clinical skills at the level of a qualified general radiologist.*" This extremely broad objective not only leads to difficulty in assessing these skills but also in terms of designing a computer-based training environment. Overall, this leads to an enormous amount of inconsistency in the training of radiology residents and therefore affects the adequate acquisition of radiological expertise.

Computerized Tutors for Radiology Training

The problem of inconsistency in radiology residency training programs has recently been addressed by the widespread proliferation and dissemination of computer-based training programs. However, these systems typically suffer from some major instructional deficits (for an extensive review of these instructional issues refer to Azevedo, Lajoie, Desaulniers, Fleiszer, & Bret, 1997). A multitude of computer-based radiology training environments has recently been developed with the objective of supporting the acquisition of radiological expertise. In general, these systems have failed to reach this objective since they: (1) lack a theoretical framework incorporating the empirical evidence from cognitive skill acquisition, medical cognition and radiological expertise, (2) are not based on adequate models of learning and instruction, (3) represent technology-driven projects employing various CBI typologies (e.g., branching CBI, multimedia, hypermedia, and WWW), (4) are based on comparison studies of learning effectiveness (between computerized instruction and traditional lectures or several CBI typologies) which lack both methodological and statistical rigor, (5) fail to include the results of authentic analyses of discourse during teaching rounds, (6) adopt behavioral objectives, instructional methods (e.g., linear tutorials), assessment techniques (e.g., multiple choice) and remediation (e.g., canned feedback messages), and (7) fail to incorporate the computer environments into existing medical curricula. This section presents the theoretically and empirically-derived computer-based radiology training environments documented in the literature.

In recent years there has been a general increase in interest in the application of intelligent tutoring systems (ITSs) in the area of medical training. The rationale for computer-based instruction is based on the assumption that the learner's cognitive processes can be modeled, traced, and corrected in the context of problem-solving (Anderson, Corbett, Koedinger, & Pelletier, 1995; Lajoie, *in press*). In recent years, several ITSs have been developed for radiology training.

Examples include the CT Brain Tutor for training radiology residents to diagnose brain tumors from CT scans (Macura, Macura, Toro, Binet, & Trueblood, 1994), and a tutor for training radiology residents to diagnose neurological MRI images (Sharples, duBoulay, Teather, Teather, Jeffrey & duBoulay, 1995). The extensive work of Sharples and colleagues (Sharples, 1991; Sharples, duBoulay, Teather, Teather, Jeffrey & duBoulay, 1994) in developing the CT and MRI tutors focuses on accounts of professional practice and skill development and how these issues influence the design of their tutors. They have used statistically-based principles and a structured image description language for teaching radiological image interpretation and the diagnosis of cerebral diseases. Their approach to visual concept tutoring is based on grouping exemplars. Their tutoring approach facilitates the novice to expert transition by assisting the residents in the progression from visual to structural schemas (facilitating rapid pattern matching) and therefore ensuring transfer of skills and learning. Lastly, their tutors aim at training radiologists to view and describe images in a systematic manner.

More recently, Rogers (1995) developed the VIA-RAD tutor based on extensive analyses of verbal protocols obtained from staff and radiology residents. The tutor is based on the integration of computer-displayed radiological images with cooperative computerized assistance for decision-making. The VIA-RAD system is a blackboard-based architecture, founded on extensive data collection and analysis in the domain of diagnostic radiology, together with cognitive modeling of the interaction between perception and problem-solving. A small prototype of the system has been implemented and tested with radiology professionals.

In sum, these ITSs are based on cognitive science principles of expertise development and incorporate tutoring interventions and tutorial dialogues that are based on analyses of human interactions. As such, an ITS approach would offer consistency and standardization in the training of mammogram interpretation. Therefore, this section presents a cognitively-based and empirically-derived approach for the design of the RadTutor, a computerized tutor for training radiology residents to diagnose breast diseases from mammograms.

The Nature of Radiological Expertise

Numerous researchers employing disparate theoretical and empirical paradigms have investigated radiological expertise. Three basic "paradigms" that have been applied widely are: (1) search studies which investigate eye movement patterns while experts and novices read x-ray films, (2) signal-detection studies which investigate the ability of novices and experts to detect normal and abnormal film findings, and (3) cognitive research aimed at eliciting the underlying cognitive and perceptual factors involved in radiological expertise. Relatively few studies (Azevedo, 1997; Faremo, 1997; Lesgold, Rubinson, Feltovich, Glaser, Klopfer, & Wang, 1988; Rogers, 1996) have actually investigated the underlying cognitive and perceptual factors involved in radiological diagnosis. As a result, a fundamental understanding of the constitution and acquisition of expertise in other radiological sub-specialties such as mammography has yet to be determined. The following section presents a brief overview of a recent study in mammogram interpretation and presents the major findings.

A Cognitive Study of Mammogram Interpretation

A recent study by Azevedo (1997) examined the problem solving strategies used by staff radiologists and radiology residents during the interpretation of difficult mammograms. Ten radiologists and ten residents diagnosed 10 cases under two experimental conditions (authentic and augmented). In the authentic condition, standard unmarked mammograms were used. Mammographic findings were highlighted on a second set of the same cases for the augmented condition. Verbal protocols were analyzed and revealed that mammography interpretation was characterized by a predominant use of data-driven or mixed-strategies depending on case typicality and clinical experience. Repeated measures ANOVAs revealed that the radiologists scanned the cases significantly faster than the residents. No group differences were found in the number of radiological findings, radiological observations, and number of diagnoses across experimental conditions. Frequency analyses revealed that regardless of experimental condition both groups (a) used the same types of operators, control processes, diagnostic plans, (b) committed the same number of errors, and (c) committed case-dependent errors. Overall, the fact that few differences were found between the groups on the various measures may be due to the fact that mammogram interpretation is a well-constrained visual cognitive task.

Implications for the Design of the RadTutor The results of this study have served as one source of empirical basis for the design of the RadTutor. The following is a brief discussion as to how the results have been incorporated into the RadTutor. The *content analyses* of the areas of breast disease and mammography have been used to construct the domain knowledge module of the prototype as a series of production rules. The *cognitive task analyses* based on extensive interviews with the domain expert were used to develop the overall instructional sequencing for each case and to build the system's expert module.

The *cognitive model* characterizing mammogram interpretation consisting of 7 steps served as the overall instructional sequencing for the system. These steps include: (a) reading a clinical history, (b) placing a set of mammograms on a viewbox and identifying individual mammograms in the set, (c) visually inspecting each of the mammograms either with or without the use of a magnifying glass, (d) identifying mammographic findings and observations, (e) characterizing mammographic findings and observations, (f) providing a definitive diagnosis or a set of differential diagnoses, and (g) specifying subsequent examinations. In addition, the system is capable of determining if the user is employing a *data-driven* and/or a *mixed problem solving strategy*. The system monitors the evolution of the user's problem solving behavior (during the resolution of a case) and predicts if he/she is engaged in one or the other problem solving strategies. This aspect of the prototype is extremely critical in identifying errors and providing the appropriate level of scaffolding.

The *problem solving operators* used by both staff and residents indicated that both groups made extensive use (76% of the time) of 4 particular operators (data examination, data acquisition, data exploration, and hypothesis generation). This information was used primarily in the design of the different levels of instructional scaffolding and interface. For example, data acquisition, examination, and exploration meant that the interface was build to display the case history (data acquisition) and set of mammograms (data acquisition) and allow the user to manipulate the images for better feature characterization or comparison (data exploration). Similarly, the system provides extensive instructional scaffolding during the hypothesis generation phase to ensure that the user has proposed the appropriate level of hypothesis (e.g., malignant versus infiltrating ductal carcinoma).

The verbal protocols analyses indicated that diagnostic planning (i.e., propose further medical examinations) was the most frequent *control process* used by the subjects. As such the interface was built so as to allow the user to list more than one medical examination. This aspect of the prototype is associated with an extensive discussion of the benefits associated with each subsequent examination.

The error analyses revealed five types of errors including:

(1) a **perceptual detection error** (failure to detect a mammographic finding),
(2) a **finding mischaracterization error** (incorrect characterization of a mammographic finding),
(3) a **no diagnosis error** (detection, correct identification, and characterization of a mammographic finding but a failure to make a diagnosis)
(4) a **wrong diagnosis error** (detection, correct identification, and characterization of a mammographic finding but proposing a wrong diagnosis), and
(5) a **wrong recommendation error** (correct detection and characterization of a mammographic finding,

and proposing a diagnosis at some level of abstraction, but proposing an inappropriate subsequent examination).

Each type of error is presently being formalized as a production rule and is integrated in the expert module. Furthermore, each error type is also associated with a specific instructional scaffolding strategy. For example, a finding mischaracterization error is associated with an instructional strategy that focuses the user's attention on the part of a mammographic finding which was mischaracterized (e.g., the border of a mass).

The process of identifying error commission is facilitated by the fact that the analyses indicated errors to be case-dependent. For example, cases with atypical mammographic manifestations are highly likely to produce a finding mischaracterization error.

Analyses of the Radiology Teaching Rounds: Eliciting Teaching Strategies

The tutoring strategies and levels of instructional scaffolding adopted in the prototype are also based on the authentic analyses of radiology teaching rounds (Azevedo, Lajoie, Desaulniers, & Bret, 1996). These analyses examined the diagnostic problem solving processes and teaching methodologies employed by a staff radiologist teaching six residents during two one-hour mammography rounds. However, this section focuses specifically on the discourse analyses of the teaching methods used by the staff radiologist during the mammography teaching rounds.

The topographical view of a typical teaching round in mammography is illustrated in Figure 1. A round is typically comprised of an expert (staff radiologist in charge of the round), residents (denoted by the circles – numbers indicate residency level), a resident who is solving a case (e.g., R3), and a set of mammograms displayed on the viewbox (including the mediolateral [MLO] and cephalocaudal [CC] views of the left and right breasts). The two arrows represent the directionality of the discourse that was analyzed. The first arrow indicates R3 solving the case that is presented on the viewbox. The second bi-directional arrow indicates the (1) pedagogical strategies that the staff radiologist used to support the resident's diagnostic problem solving and (2) the resident's request for various levels of support from the staff radiologist. The results of the analyses are presented below.

The teaching methods used by the staff radiologist during the breast disease rounds including *coaching*, *scaffolding* and *fading*, and *articulation* (similar to the teaching methods advocated by the proponents of cognitive apprenticeship) are presently being incorporated into the RadTutor. Occasionally, the radiologist would also provide *coaching* and support. In the case of intermediate residents, the radiologist would provide scaffolding during the diagnostic process in the form of hints, redirecting their viewing

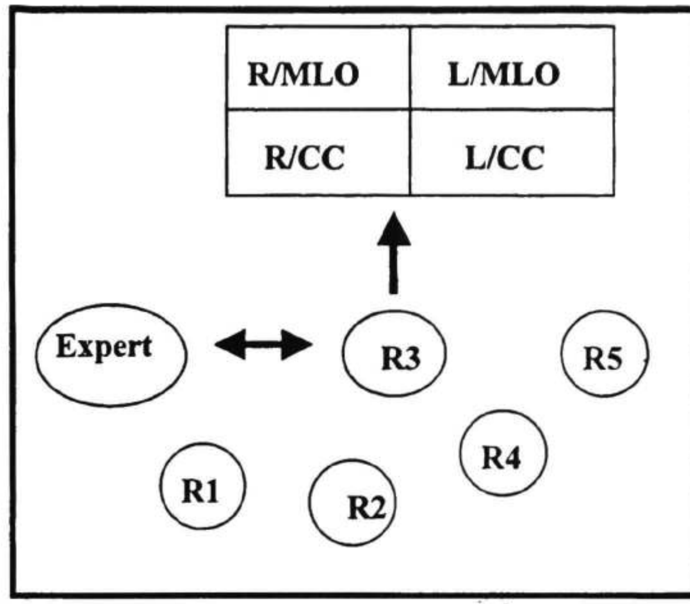

Figure 1. A topographical view of a typical radiology teaching round.

process, and subsequently fading all instructional support when the resident demonstrated the capability to pursue the task on his/her own. In the RadTutor, *coaching* and hints are provided through text messages, pop-up text messages, and highlighting of mammographic findings and observations. In addition, multiple levels of instructional *scaffolding* have also been delineated based on the results of the dissertation and interviews with the expert staff radiologist. The finest illustrations of *articulation* were observed when the radiologist externalized her reasoning process beginning with the assignment of probabilities to pathological features, followed by the systematic elimination of competing differential diagnoses until the definitive diagnosis was achieved. This teaching method was especially valuable since all residents may potentially benefit from the externalization of the expert's diagnostic problem solving. In the RadTutor, articulation is being implemented by using digitized video clips of the expert staff radiologist diagnosing a case while the tutoring system highlights the mammographic findings and observations on the digitized mammograms.

In summary, this section has presented a cognitively-based and empirically-derived approach for the design of the RadTutor. The design approach is based on (1) Azevedo's (1997) study of problem solving in mammogram interpretation and (2) the tutoring strategies elicited during radiology teaching rounds.

Bridging the Gap: Deriving Instructional Principles from Cognitive Science and Empirical Studies

The following section delineates instructional principles derived by integrating the empirical research on medical cognition, radiological expertise, mammogram interpretation, and analyses of radiology rounds. The successful integration of these several sources of evidence are critical to the design of a theoretically-based and empirically-derived prototype for training both residents and staff radiologists in the interpretation of mammograms. Each of the four instructional principles posited is supported by existing theoretical and empirical evidence described previously in this paper. The instructional principles incorporated in the mammogram interpretation prototype include the principles of (1) multiplicity, (2) activeness, (3) accommodation and adaptation, and (4) authenticity (for an extensive overview of some of these principles for supporting computer-supported problem-based learning see Koschmann, Kelson, Feltovich & Barrows, 1996).

The **principle of multiplicity** is based on the concept that knowledge is complex, context-sensitive, inter-related and thus instruction should promote multiple perspectives, representations and strategies. This principle is based on the theory of cognitive flexibility (Spiro, Feltovich, Jacobson, & Coulson, 1991) in medicine that emphasizes the use of multiple knowledge representations and repeated exposure to instructional content. According to this principle, single mental representations and unitary learning approaches are insufficient for (1) capturing the nature of complex instructional materials and (2) knowledge application in ill-structured domains (such as radiology). A recent study examining the effectiveness of hypermedia versus traditional lectures in radiology has demonstrated the use of multiple knowledge representations through the use of text, digitized video clips and animations of radiology physics concepts do facilitate learning and knowledge application (Shaw, Azevedo & Bret, 1995). The RadTutor provides the resident with a stock of breast disease cases that can be accessed in a structured manner according to diagnostic categories, specific mammographic manifestations (i.e., findings and observations), and relevant clinical history cues.

The **principle of activeness** is based on the concept that learning is an active process, requiring mental construction and manipulation of the subsymbolic (e.g., gray-scale densities exhibited on mammograms) and symbolic representations (e.g., clinical findings exhibited on mammograms and relevant clinical history findings) that comprise the task environment. Therefore, instruction fosters knowledge construction through problem-solving activities that lead to the development of skill acquisition. This principle reflects the nature of learning through active construction of knowledge facilitated by problem-solving activities. Effective instructional methods should promote planning, reasoning, goal-directed problem-solving, and reflection. This principle reflects the empirical findings in the areas of cognitive skill acquisition (VanLehn, 1996) and the development of expertise (Ericsson & Charness, 1997; Ericsson & Lehmann, 1996). In the RadTutor, instruction fosters knowledge construction through meaningful problem-solving activities that facilitate skill acquisition and the development of expertise.

The **principle of accommodation and adaptation** is based on the concept that the learning process is to a large degree affected by the extent of the learner's existing knowledge. As such, instruction facilitates adaptability by building upon the learner's existing knowledge, monitoring learner progress and rectifying misconceptions when they arise, and fostering the development of metacognitive skills. A rule-based domain knowledge module and a student modeling approach are presently being considered based on the well-constrained nature of the domain of mammography.

The **principle of authenticity** is based on the concept that learning is sensitive to contextual factors, which determine the usability of what is learned, and the extent of skill transfer. Therefore, instruction should provide learning activities that are required in the domain, that are valued in the real-world context, and that emulate the real-world environment as much as possible. This principle reflects the recent claims by advocates of situated cognition (Greeno, 1998) regarding the need to study the contextual and situational aspects of the cognitive phenomena being studied. In the RadTutor, the problem-solving activities resemble what is routinely encountered in a resident's work environment. For example, it provides the tools typically used to solve mammogram cases (such as a magnifying glass and a ruler to measure masses and lesions).

Conclusion

This paper outlined the cognitively-based and empirically-derived conceptual framework for the development of the RadTutor, a prototype computerized tutor to train radiology residents in diagnosing mammograms. The conceptual framework is based on the results of: (1) a recent cognitive study of mammogram interpretation (including the cognitive model of mammogram interpretation, the problem solving strategies used by staff radiologists and radiology residents, and the typical case-related errors), (2) a critical assessment of the haphazard nature of radiology residency training programs, (3) a review and critique of existing computer-based radiology training environments, (4) an analysis of authentic radiology resident teaching rounds, and (5) instructional principles for the design of the mammography tutor.

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