

## Analysis of a Mammography Teaching Program Based on an Affordance Design Model<sup>1</sup>

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### **Abstract:**

**Rationale and Objectives.** The wide use of computer technology in education, particularly in mammogram reading, asks for e-learning evaluation. The existing media comparative studies, learner attitude evaluations, and performance tests are problematic. Based on an affordance design model, this study examined an existing e-learning program on mammogram reading.

**Materials and Methods.** The selection criteria include content relatedness, representativeness, e-learning orientation, image quality, program completeness, and accessibility. A case study was conducted to examine the affordance features, functions, and presentations of the selected software. Data collection and analysis methods include interviews, protocol-based document analysis, and usability tests and inspection. Also some statistics were calculated.

**Results.** The examination of PBE identified that this educational software designed and programmed some tools. The learner can use these tools in the process of optimizing displays, scanning images, comparing different projections, marking the region of interests, constructing a descriptive report, assessing one's learning outcomes, and comparing one's decisions with the experts' decisions. Further, PBE provides some resources for the learner to construct one's knowledge and skills, including a categorized image library, a term-searching function, and some teaching links. Besides, users found it easy to navigate and carry out tasks. The users also reacted positively toward PBE's navigation system, instructional aids, layout, pace and flow of information, graphics, and other presentation design.

**Conclusion.** The software provides learners with some cognitive tools, supporting their perceptual problem-solving processes and extending their capabilities. Learners can internalize the mental models in mammogram reading through multiple perceptual triangulations, sensitization of related features, semantic description of mammogram findings, and expert-guided semantic report construction. The design of these cognitive tools and the software interface matches the findings and principles in human learning and instructional design. Working with PBE's case-based simulations and categorized gallery, learners can enrich and transfer their experience to their jobs.

**Key Words.** Mammogram reading; image; affordance design; e-learning; perceptual problem solving.

### **Article:**

Breast cancer is the most common cancer among women in the United States and the leading cause of cancer deaths for women between the ages of 20 and 59 years. Screening mammography is the current main approach

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for early detection of nonpalpable breast cancers (1). The early detection of breast cancer depends on the accuracy of mammogram interpretation. Literature suggests the need to educate radiologists for high-quality women's medicine. Screening volume is increasing, and the number of radiologists, especially newly trained radiologists who feel comfortable and competent in screening mammography, is decreasing (2,3).

Further, studies suggested variations in the expertise of mammogram interpretation related to the amount of training: After assessing current mammogram training in residency programs, Gillian M. Newstead (3) confirmed results from others who found higher rates of false negatives and false positives in readers with less training and experience (4).

Therefore, the seriousness of the disease and the scope of mammography call for expert radiologists and quality training materials. Reports continued to document the importance of advanced training and experience for radiologists in order to detect and diagnose breast cancer on mammography (5). Responding to this demand, some computer-based training programs and systems have been developing to complement the traditional mixture of ad hoc apprenticeship and lectures. They include video applications (6), hypermedia-based programs (7), and teaching files on the World Wide Web (8,9). They offered useful components to blend with the traditional textbooks, conferences, and lectures.

However, there is no consensus on how to evaluate these new technologies. The widespread use of computer technology in education asks for courseware evaluation, but it leads to some inappropriate approaches. One of the examples is the media-comparative study (10,11). These studies compared the delivery technology in e-learning programs (computer-based instruction, hypermedia learning, or Web-based training) with traditional media. Usually, no significant differences were found. The studies are problematic because they included too many variables when they study media. These variables confound media effect. Therefore, we may study e-learning programs in other ways rather than the comparison of technologies as delivery media. For example, Cook (11) suggested that we conduct e-learning research comparing different configurations, methods, and presentations rather than media.

Some others conducted formative and summative evaluation studies on the technology-based/technology-supported educational programs, which are either performance tests or learner attitude surveys (12). Some of the problems of existing evaluation models include overlooking the relationship between the design of technology and the human cognitive processing in learning, using former evaluation models in traditional class teaching without modification, and lacking mechanisms to evaluate whether the technology fits into the principles of human learning. Specifically, the evaluations usually just focus on the results of learning but ignore the cognitive processes of learning with technology. Although learner attitude and performance have been included in the assessment, these aspects do not identify what the learner does with technology and what the technology does in the learning process. One of the basic principles in instructional design is that learner is the center of learning and learner's mental participation in learning is critical (13). Therefore, an inquiry into technology-mediated learning process is necessary in evaluation.

Technology itself is not necessarily good for learning. For example, graphics do not necessarily support learning if the static or animated imageries are not related to what is learned. Technology-centered approaches in instructional design are detrimental to instructional design (14). On the other hand, researchers in human cognition and learning inspire us to examine learning programs from new perspectives. The affordance design model (13) is one of them. First introduced by J. J. Gibson (15), affordance refers to the "features that the environment provides to the individual" (13). Integrating behavioral and cognitive perspectives, the affordance approach takes both the environment and the information processing into consideration. The behavioral perspective suggests that people learn through responding to the stimuli in the environment. At the other end of the spectrum, the cognitive perspective emphasizes the role of information processing in learning. The affordance model integrates the environment and mental process, the factors both internal and external to the individual. The designed affordance of educational technology means "the properties or functions of technology that foster learning" (13). This model suggests that the evaluation can examine if the properties and/or functions

of the learning environment extend the individual's capabilities in learning and interact with the cognitive process of the individual. It is consistent with one of the major principles in human learning (16): the external learning condition is supposed to match the internal condition. Here the external condition refers to the learning environment designed for the learner, while the internal condition means the learner's characteristics, including the learner's cognitive processes in learning.

Also, the affordance design model includes the examination of human-computer interactions. It investigates how the user feels about the interface of the program. The reason is that human—computer interactions also indicate how well the design is in facilitating the learning process. Different from the above-mentioned component of affordance design, the human—computer interaction emphasizes the relationship between the presentation of information and the learner's use of the presentation. However, the above affordance design component places greater emphasis on supporting and extending the learner's cognition in knowledge acquisition and skill development.

Therefore, the purpose of this study was to examine an existing e-learning program in mammogram reading and review the properties and functions of the learning environment that may or may not probably interact with, facilitate, and extend the cognitive and practice processes of the individual. It was to study the interaction between the learning process and the learning environment, including the design of the properties, functions, and its presentation. The purpose of this case study was not to construct theories but to assess whether the courseware is consistent with the affordance design and human learning models. Here are some research questions the study sought to answer:

1. What features and functions does the computer technology design of the studied mammogram reading educational software offer to enable or constrain mammogram reading learning?
2. What are the interactions between these features and functions and the learner's cognitive and practice processes in mammogram reading?
3. What level of ease does the learner have in using this educational software?
4. How well is the human—computer interface design of the program grounded in design heuristics?

## MATERIALS AND METHODS

### *Materials*

The program selection criteria are content relatedness, representativeness, e-learning orientation, image quality, program completeness, and accessibility. The selected program, "Mammography: Practice-Based Education" (PBE) (17), was designed, programmed, and implemented by a team of radiologists, computer scientists, university professors, and the other support personnel. The program presents selected, full resolution, and proven mammography cases. Over 200 cases are available for study. The CD-ROM program includes current applications of screening mammography including benign and suspect calcifications; benign, indeterminate, and suspicious masses; special cases; and associated findings. To maximize the program's performance and image quality, the Windows-based program requires these minimum computer specifications: 500 MHz Pentium III or faster processor, 256 MB RAM, minimum 1024 X 768 pixels for video display, 40 MB free hard drive space, and operating systems of Windows 98, Windows 2000, Windows NT (with MS service pack 6), or Windows XP.

### *Participants, Instruments, and Procedures*

A case study (18) was conducted to examine the designed and programmed affordance features and functions of the mammogram reading software and the interaction between these features and functions and the learner's cognitive and practice processes in mammogram reading. The e-learning program was studied intensively to explore if and what features and functions its technology design created to enable capabilities in mammogram reading skills.

Two rounds of interviews (19) were conducted as well as an in-depth document analysis of the courseware. The interviewee was a senior radiologist with more than 10 years of mammogram reading experience. The interview

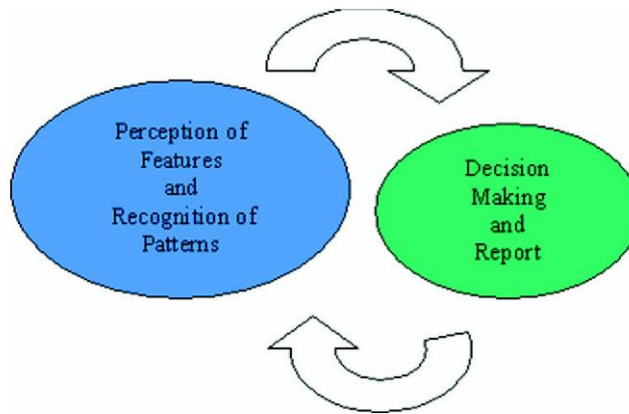
questions were developed based on some existing research studies in radiological expertise and mammogram reading. The interviews were semistructured, so the interview questions were flexible corresponding to the interviewee's responses. The first interview dealt with the cognitive processes involved in mammogram reading. The second interview asked some follow-up questions for member checking (20). Interview schedules with some grand-tour questions and descriptive questions were prepared and used in the interviews. Interview data were analyzed with the following steps: clean, unitization, reduction of data, coding, etc. The constant comparison data analysis method (21) is used here.

Document analysis (22) was conducted examining the features and functions of the program as well as the relationship patterns between the features of the courseware and the learner's cognitive processes in learning. After becoming familiar with the format of the courseware, the major module of the courseware was determined as the unit of analysis. Then some categories were listed to construct a protocol of data collection. The categories included modules, learning tools in each module, the features and functions of the tools, and the relationship between the tools and the learner's cognitive processes. The courseware was loaded onto a high-resolution computer satisfying the requirements of the courseware. After the interviews and the document analysis, some results were derived of the cognitive processes of mammogram reading and the features and functions of the software. Some patterns and themes were discussed afterward. Data were read and examined repeatedly for data coding and conceptual refinement. Summaries of findings were then integrated to a report.

Triangulation (23) was used to find the evidences about if and what interview-derived cognitive processes are consistent with the processes identified in previous studies. Triangulation also provided evidence of the congruent relationship between the cognitive processes of mammogram reading and the tools provided to interact with the processes, especially the processes that may exhaust the learner's cognitive resources.

The case study also included heuristics in usability test and inspection. As one of evaluation approaches, usability establishes the effectiveness and satisfaction with which users can achieve tasks in a particular environment, defined by the International Standards Organization (24). It examines the degree to which a program is easy to learn, pleasant to use, and contains the necessary functionality to allow the user to complete the tasks for which it was designed. Three end-users as evaluators participated in the test with their talking what they thought about the software while using it. The think-aloud session included the following four procedures: set up the computer and the software on the computer in a quiet environment; guided the end-users to talk about the issues of navigation, layout, instructional aids, pace and flow of information, and aesthetic appeal before they used the program; asked the user to carry out some prepared tasks and talk aloud what happen in the process of using the program; and observed and took notes of what the users talked about their ease, confusion, or other reactions through the process of using the software and did the tasks. Besides, an instructional designer conducted an analysis of the product, identifying problems with the software based on usability heuristics and past experience with similar products. The design heuristics adapted two models by Nielsen (25) and Quinn (26). The heuristics function as general guides or rules of thumb. Since software of any type is supposed to follow these basics for usability compiled by Nielsen, these rules are also applied to educational software. Quinn's heuristics were based on learning theories, such as cognitive apprenticeship and anchored instruction.

Some statistics were calculated. The frequency of tools of certain enabled or constrained features and functions was calculated. Also, the percentage of each type of tool supporting the cognitive processes was determined. The results of these calculations were used to decide if the affordance design meets the demands of cognitive processing in mammogram reading. The cognitive processes were examined mainly through the interview, while the affordance design was investigated through the document analysis.



**Figure 1.** The cognitive processes of mammogram reading.

## RESULTS

### *Interview Results*

The analysis of the interview transcripts indicates the mental processes of mammogram reading generally consist of two components: perception of features and patterns and decision making according to various data provided and evidence verifying each other (Fig. 1).

The first component perception includes the following subcomponents: 1) Check identity, correct display, and read history. Identify projection and display problems, exposure problems, and technical issues; 2) check density category; 3) survey for overall symmetry, skin thickness, lymph nodes, and incidental findings such as artifacts; 4) survey for masses (there is a methodology to do this); 5) survey for calcifications; 6) triangulate (localize) findings, correlating with one another on multiple projections; and 7) compare with prior mammograms if available, correlating with other imaging and physical findings. The second component making decisions is carried out through the following subcomponents: 1) Formulate a diagnosis for each finding, and formulate a management plan if applicable; and 2) formulate a clinical report to dictate, review, and be approved.

Screening mammogram reading emphasizes the perception component of the cognitive process. The nature of screening mammogram reading is perceptual, including optimizing the digital image display environment, searching the image for related features, and detecting the patterns of related features with verifications. The decision-making stage is grounded in the perceptual stage.

### *Document Analysis Results*

The examination of PBE identified that this educational software designed and programmed some tools

**Table 1**  
**Functions of PBE Corresponding to Features of Affordance Design**

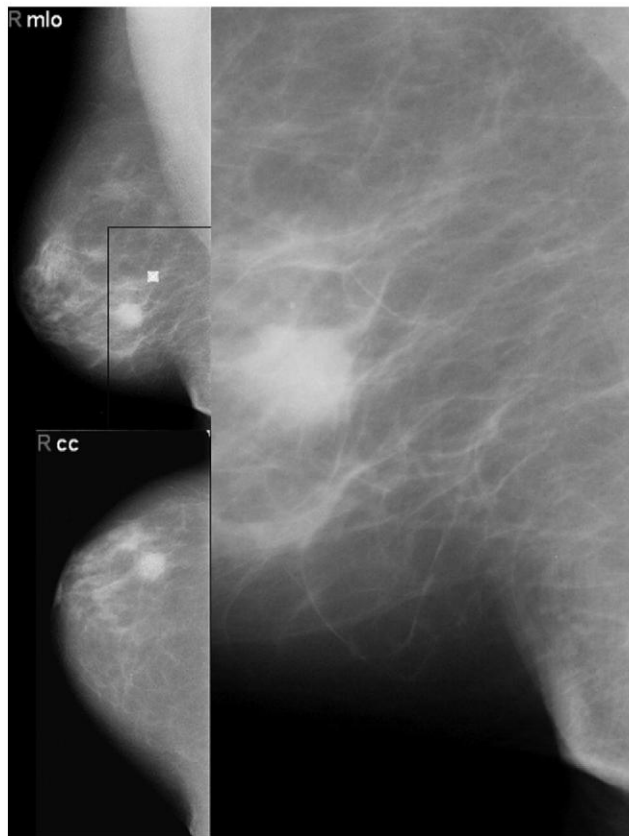
PBE Function	Type of Interaction Feature of Affordance Design			
	Visualization	Conceptual	Decision Making	Constructive
Display optimization	x			x
Zoom	x			x
Pan	x			x
Polarity	x			x
View comparison	x		x	x
Measurement	x			x
Marker	x			x
Brightness and contrast control	x			x
Narrative report		x	x	x
Individualized comments and recommendations		x	x	x
Expert comparison report		x	x	x
Case discussion		x	x	x
Definitions and examples		x		x
Immediate feedback			x	x
Teaching links				x
Optional outcome audit			x	

**Table 2**  
**The Number of Tools Supporting Cognitive Processes**

Cognitive Processes	Types of Tools			Total	Percentage
	Visualization	Conceptual	Decision Making		
Perception and pattern recognition	8	5		13	65%
Decision making			7	7	35%

(Table 1). The learner can use these tools in the process of optimizing displays, scanning images, comparing different projections, marking the region of interests, constructing a report, assessing one's learning outcomes, and comparing one's decisions made with the expert's decisions. Besides, PBE provides some resources for learners to construct their knowledge and skills, including a categorized image library, a function of searching terms, and some teaching links.

1. *Feature survey, observation, and comparison tools/ projection tools*: The program provides nine projection buttons to access nine different image arrangements (Fig. 2).
2. *Feature observation tools* (Figs. 3 and 4):
  - *Flip*: Set RMLO/RCC to left, and vice versa.
  - *Feature quantifying tool*: Measure features in centimeters.
  - *Feature observation tool (polarity)*: Shift black to white and vice versa.
  - *Attention tool*: Mark the attended features and region of interests.
  - *Feature observation tool*: Click and hold in an area of interest, which can be zoomed in for more detailed observation.
  - *Brightness and contrast adjustment tool*: Use scroll-bars to fine-tune brightness and contrast. The defaults show suggested brightness/contrast levels.
3. *Self-assessment tools*: The comparison page allows the learner to compare his or her report against the established report.
4. *Constructive tools*: The glossary is a list of every linked term within the course. Once a term is selected, all instances of it within the course can be found with a search. The term will appear in the search field. The



**Figure 3.** Marker and zoom tool.

gallery provides a survey tool to review all the related images put under the same category. It is helpful to construct perceptual knowledge.

In addition, the study was triangulated among the interview results and the documentary analysis results. This derived some results of the alignment between the cognitive processes and the cognitive tools created and provided by PBE software (Table 2). Most of the tools (65%) support the perceptual process of data, while some decision-making tools are (35%) offered.

#### *Usability Test and Inspection Results*

The usability tests and inspection identified what the users and the instructional designer feel about the software when they use and implement it. They found the ease of human—computer interaction in using PBE.

The users found it easy to navigate and carry out tasks. The users also reacted positively toward PBE's navigation system, instructional aids, layout, pace and flow of information, graphics, and other presentation design.

The instructional designer assigned high grades to its interface design and instructional strategies (Table 3).

#### **DISCUSSION**

The study revealed much on PBE's functions, features, and interface. Overall, its instructional design supported,

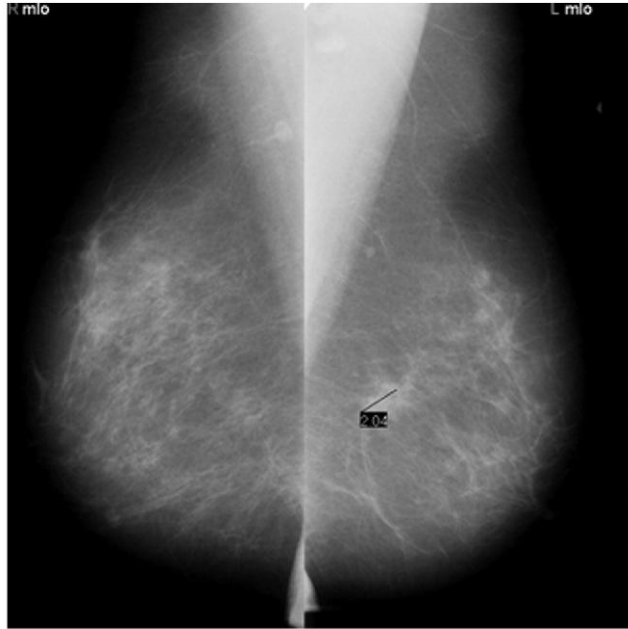
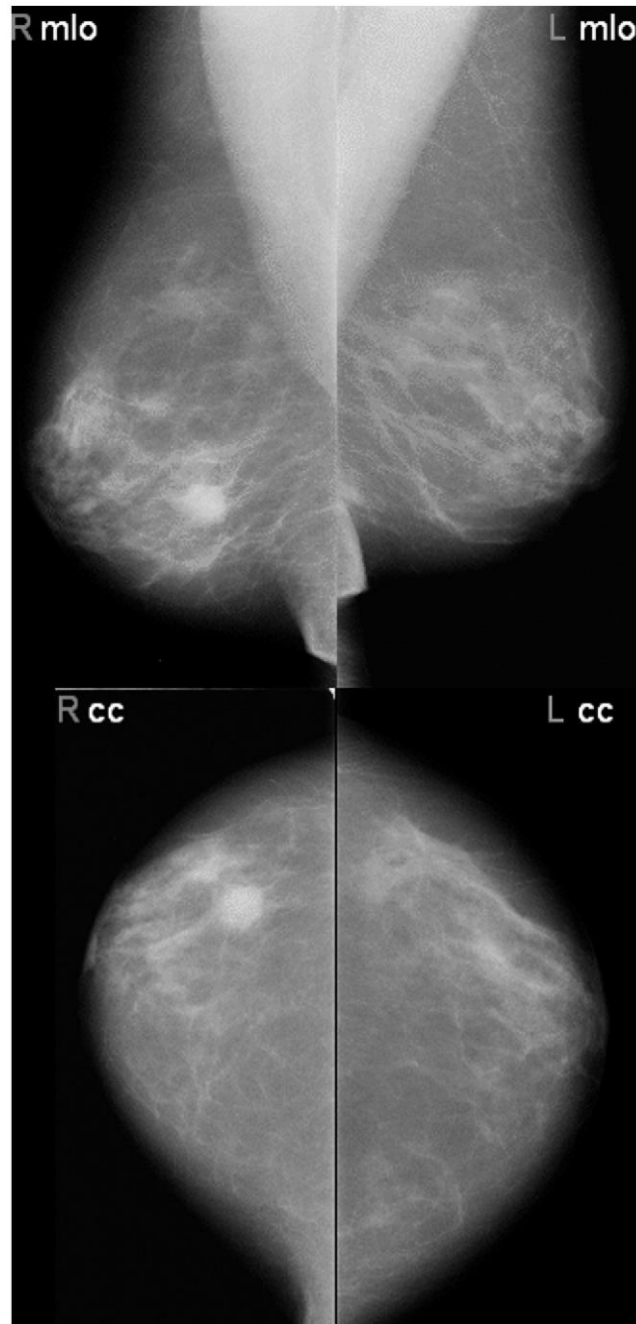


Figure 4. Measurement tool.

**Table 3**  
**The Results of Usability Test (heuristics based on Nielsen and Quinn)**

Learning Interface Design Heuristics	Yes (Y) or No (N)
Ensures visibility of system status	Y
Maximizes match between the system and the real world	Y
Maximizes user control and freedom	Y
Maximizes consistency and matches standards	Y
Prevents errors	Y
Supports recognition rather than recall	Y
Supports flexibility and efficiency of use	Y
Uses aesthetic and minimalist design	Y
Clear goals and objectives	Y
Context meaningful to domain and learner	Y
Content clearly and multiply represented and multiply navigable	Y
Activities scaffolded	Y
Elicits understandings	Y
Formative evaluation	Y
Support for transference and acquiring self-learning skills	Y





**Figure 2.** The four-view image arrangement.

facilitated, and extended the learner's cognitive processes. The users thought it was easy to use. They liked the interactive projections, prompt feedback, and the other tools.

Although the process of mammogram reading may relate to different operators, it is perceptual problem solving in nature. At least two reasons can be listed here:

First, the tasks of mammogram reading require the reader to perform by applying perceptual concepts and principles in new situations. Second, the concepts and principles are based on perceptual features and patterns and the problems are perceptual problems. This finding is consistent with what literature indicates about the perceptual nature of mammography interpretation (27,28). After clarifying the nature of mammogram reading, some discussions of PBE program take place as follows:

### *Cognitive Tools*

The learning environment PBE designed and programmed is grounded in the cognitive problem-solving model of the learner. The features and functions of PBE's affordance design facilitate learning by making thinking visible to the learner and supporting perceptual problem analysis, solution, and feedback. The study results indicate that PBE provides the learner with some cognitive tools, supporting their perceptual problem-solving processes and extending their perceptual problem-solving capabilities. The use of the following tools required active mental participation from the learner, thus learning occurs in the learner through applying these tools to solve problems.

### **PBE's perceptual tools**

The software provides some perceptual tools that facilitate the learner to observe and compare the features among different projections. The variety of image arrangements provides some perceptual possibilities: First, the learner can have more ease in evaluating the symmetry of the right and left breast through different kinds of mirror-fashioned image arrangements. The projection button tools juxtapose the images in different ways so that the learner can compare features more easily than just see one image once. According to perceptual psychology, mirror images can facilitate the eye to more easily perceive asymmetric densities than side-by-side images (29). Second, the constant scrutiny of different projections lets the learner continuously compare the features across images. This facilitates the learner to develop mental models representing the features. Third, the tools facilitate both the global and detailed view of the images. The projection button of the four-view images (RMLC, LMLC, RCC, LCC) shown on one screen first presents an overview. The other projection buttons can give more detailed views of the breast. The other perceptual tools, such as marker tool and zoom tool, can help the learner work with details of the image. The marker tool is also very helpful in directing attentions of the learner. Perceptual psychologists have established that the selectivity of attention (30) is critical to visual processing. Attention may be blinded or distracted to negatively affect learning results. So the attention device helps the learner keep in the region of interests in scrutinizing features. Also the program provides zoom tools to zoom in the image so that the details can be watched more closely. Fourth, the program develops a "polarity" tool for inversing colors to black and "flip" tool for the image to the other position. The polarity tool can facilitate the observation of figure and ground of the image. The previous studies in perception indicate that figure-ground segregation influences perceptual organization (31). So to speak, these perceptual tools can spare some mental resources for the learner to scan and compare features, observe the features both globally and locally, triangulate among images to find evidences for detection and later decisions, and become more attentive and sensitive to related features. These perceptual tools can allocate the learner's cognitive resources to more important tasks. They enable the learner to better utilize his or her resources to expand opportunities of detecting and making decisions. Offering opportunities of surveying and observing features across different image arrangements with details and focused attention, these perceptual tools sensitize (32) relevant features and enrich the learner's perceptual experience. The use of these tools enables performance changes in the early stages of information processing in mammogram reading.

### **PBE's conceptual tools**

Among the existing mammogram learning materials, researchers found the lack of supports for concept learning in mammogram reading (33). This investigation found that PBE supports learning the association between sets of features and categories. It provides useful conceptual tools in the format of reports and definitions. The report construction functions as an interface for the learner to come back and forth between their mental models of perceptual features and concepts they are working on. The clearly spelled-out features through report construction help the learner to code features in their memory. This helps improve the capability of pattern recognition and perceptual concept formation. Through interactively constructing semantic description of various features and concepts, learners can code and retain the perceptual patterns of features they just detect by reading the images and using those perceptual tools. They can in this way organize their feature information under different categories of normality and abnormality, which give the features meaning. This report construction can also help them define different concepts by mentally participating in the detection and decision-making processes. Besides, the definitions of terms can help the learner study concepts in an authentic context. This can facilitate the integration of instances and the features of instances into concepts.

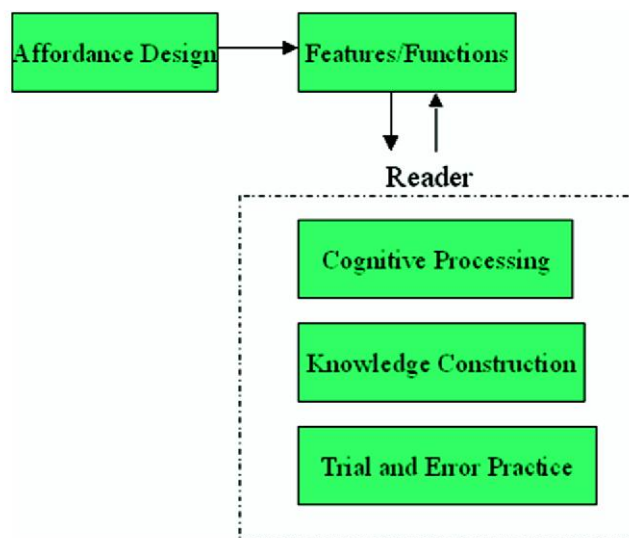
### **PBE's individualized self-assessment tools**

The program provides not only instructional tools but also self-assessment tools for the learner to continuously test his or her knowledge and skills. The self-assessment tools also include juxtaposed comparison between the learner's results and the experts' opinions. Also, the program reinforces the recommended decisions by intelligently marking the differences between the learner's decisions and the experts' decisions. This timely feedback optimizes the learning environment. In real-life clinical learning setting, feedback may be limited and lag behind because of the workload in the clinic. Also, PBE feedback includes highlighted and linked terms to more detailed concept presentation. This facilitates the remedial process in learning.

### **Discrimination -facilitated image gallery**

The PBE program provides a learning library. The learner can compare and contrast different features among and within one category by going through the image instances under similar categories. The learner can access a cohort just by clicking on the left side icon. This ease of an overview of various instances of a concept can very well facilitate the learner in feature discrimination and concept formation. The gallery extends the learner's capabilities in defining related features under a category. Scanning and skimming the images can sensitize the dimensions and organizations of related features of a category.

In brief, these tools engage different aspects of the learner's mentality in mammogram reading. The perceptual tools support both the macro and micro observation of different representations and comparison and contrasts across different projections. They also decrease the learner's inattentional blindness (34). The conceptual tools facilitate the interactions among cells in charge of perception and conceptual formation in the learner's brain. The self-assessment tools provide adaptive learning opportunities leading to self-directed learning. The gallery tools extend the capacities in conceptualization by integrating more instances under one category. These cognitive tools



**Figure 5.** Relationship between PBE's design and the learner/reader.

in PBE can be applied to other medical imaging teaching environment. The company also had a PBE program for PET-CT.

### **Pattern Matching**

The design of these cognitive tools and the software interface matches findings and principles in human learning and instructional design (13, 16). The affordance design of PBE reflects some basic principles in human learning (Fig. 5). Two of the basic principles were learner-centered learning principle and the conditions of learning.

Learner-centered learning principle suggests that learning is learner-centered but not technology-centered. Learning takes place in the learners' brain through what they do. Learning does not depend on what media is used but depends on what the learner is thinking and doing with the course materials. PBE provides the learner with the cognitive tools, involving the learner in scanning, perception, detection, conceptualization, and making decisions. These tools involve the learner in the process of actively constructing different kinds of knowledge and skills. Not only these tools make it possible for the learner to actively interact with PBE, but the ease of using the interface also impacted the learner's motivation to learn and participate in active mental processes.

The other important principle PBE matches is the conditions of learning in instructional design (16). It implies that instruction will facilitate learning when it supports the internal stages of information processing. The study results indicate external conditions aligning with internal conditions. On one hand, the interview data indicate some specific difficulties that influence the learning trajectory of mammogram reading. These are classified into two categories, including perceptual and conceptual difficulties. Also, the interviews with the radiologist indicate the nature of perception of mammogram reading. On the other hand, the perceptual tools help the learners make sense of their observations and smooth the way of their initial ideas to facilitate the process of inquiry. The learning environment provides with rich perceptual experience, engaging the learners in observing and extracting features and forming their mental representations. Also, the semantic report construction supports the learner to form some important concepts and make decisions. The different cognitive tools identified indicate that PBE highly support the processes of learning, including the cognition, construction of knowledge, and the trial and errors in practice.

The results of the usability test also indicate that PBE program is characteristic of quality interface design and instructional design. For example, the program has high-level interactivity and feedback. The program interacts with the learner in his practice of skills in pattern recognition and conceptualization. It provides individual feedback of his performance to guide the learner.

### *Simulation as an Educational and Assessment Tool*

Simulation-based programs have started to show their effectiveness in teaching and assessing complex skill sets related to a variety of jobs (35, 36). Incorporating newly developed pedagogical methods and computer technologies, PBE simulated actual practice of mammogram reading. Similar to some flight simulators, such as Microsoft Flight Simulator (36) and some diagnosis simulations (35), PBE program created a typical perceptual problem-solving simulation. PBE developed underlying expert models, helping the learner build up and internalize his or her mental models by inputting variables and receiving output data dynamically in the simulated system. The system provides an integrated simulated case-based learning environment for both teaching and assessment. Testing via simulation is showing evidence in benefiting medical education by both guaranteeing patient safety and providing test performance in authentic/real-life—like situations (36). PBE is one of the representatives of a simulation-based assessment and training system. It requires the learner to act out what he learns rather than just answering some multiple-choice questions. With embedded self-assessment, the program includes clinical outcome and pathology data. Also, the case content was representative of actual practice, with a balance of negative and positive cases. Learning by experimenting on the cases in a real-life situation, the learner can easily remember what he or she does and retrieve the case if coming across a similar problem in the future (37). By learning and self-assessing in an authentic environment, the learner can be more aware of the actual working demands and transfer what he or she learns more efficiently.

### *Affordance Model*

The affordance model was used as the theoretical basis and methodological underpinning in this study. Some researchers, such as Mayer (38) and Liu and Bera (39), have provided empirical evidence of effectiveness of the programs designed and evaluated based on this model. The outcome measures in these studies identified that learning occurred when the learning space supported and extended the learning process. Therefore, this can be a valid model in evaluating e-learning programs, although more studies are necessary to optimize procedures.

Through the cognitive task analysis, member checking, and triangulation, this study identified the learner's cognitive processes in mammogram reading. By the document analysis and usability test, it explored the relationship between the cognitive process and the tools in the learning space. In improving the validity and reliability of the findings, the study used criteria (40), including usefulness, researcher positioning, triangulation, member checking, long-term observation, representativeness check, and coding check. Since the case we chose is a representative of the phenomenon of mammogram reading e-learning program, the results of this study may be generalizable to the other cases (40). Besides, the generalizability of the case study depends on readers (40). In the future, more data need to be collected on the learning process, learner's behaviors in using PBE tools, and the performance after using these affordances.

With a learner-centered approach, PBE designed and developed a resource rich and experience authentic learning environment. It fosters and supports learning in mam mogram reading with its representative cases, cognitive tools, instructional strategies, underlying mental models, and well-designed interface. Its cognitive tools support and extend the learner's perceptual and decision-making processes. The various affordances of PBE program highly interact with the learners' cognitive processes and enable learning to occur. These tools also help learners continuously construct their perceptual knowledge and increase their perceptual problem-solving strategies through its expert model and self-assessment. The learner can internalize the mental models in mammogram reading through multiple perceptual triangulations, sensitization of related features, semantic description of mammogram findings, and expert-guided report construction. Working with PBE's case-based simulations and categorized gallery, the learner can enrich and better transfer his or her mammogram reading experience with expert feedback and conceptual knowledge organization. The analysis of PBE on the basis of affordance design leads to the conclusion that PBE is a valuable e-learning program and PBE approach is a widely applicable approach in teaching medical image reading.

## NOTES

Practice Based Education is a trademark of Efficiency Systems, Inc. The program was developed by the Efficiency Learning Systems division, which provided copies of the mammography teaching program for review, but did not influence the design or analysis of this research.

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