The Cognitive Basis for an MR Image Tutor

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Abstract: We present an approach to the design of computer-based learning and support systems that calls on findings from cognitive science and educational psychology to provide initial design guidelines. These can supplement task analyses and user requirement studies, by providing a rationale for the cognitive constraints and educational goals of the system. We describe the design and prototype implementation of a Tutor for medical images, based on guidelines from prototype category theory, the psychology of concept teaching, and statistical modelling of category membership. The guidelines could be applied more generally to the development of other computer-based tutors for visual concepts.

Introduction

A project involving the University of Sussex, De Montfort University (Leicester) and the Institute of Neurology (London) is developing a computer-based tutoring system to assist the training of radiologists in diagnosis of Magnetic Resonance (MR) images of the brain. The project has brought together expertise in cognitively informed system design, statistical modelling and medical image description. The aim is to:

- supplement professional training in radiology by offering computer-based tutoring and diagnostic assistance;
- provide trainee radiologists with exposure to a large structured library of medical images and associated descriptions;
- help radiologists to develop a 'conceptual framework' and appropriate image description language for image interpretation.

The Institute of Neurology in collaboration with the Medical Systems Group at De Montfort University, has developed a description language for MR images of the head suitable for a wide range of image sequences. The language has been incorporated in a computer tool which allows an expert rapidly to generate descriptions of sample images. The team has established a dedicated computer archive of some 1121 cases which illustrate a wide range of pathologies. Each image is accompanied by a description, in the form of a vector of image feature values, supplemented by follow-up/biopsy/autopsy information to provide confirmed diagnoses. This archive will provide domain knowledge for the MR Tutor. The Tutor will allow a trainee radiologist to browse through a set of extensively annotated images, to learn the image description language, to practise case-based diagnosis, and to call on computer assistance when reporting on new patients.

Cognitive Support Systems

The traditional approach to ITS design, of communicating domain knowledge by means of an instructional dialogue, is not appropriate to many areas of professional expertise. A trainee in a profession such as radiology is knowledgeable and self-directed, and would be better helped by a mixture of case-based learning and practice in work-related skills. Research in the School of Cognitive and Computing Sciences at the University of Sussex has been directed towards 'cognitively informed' system design. The aim is to use studies of human cognition to provide requirements for the design of highly interactive 'cognitive support systems', which can be used by professionals to aid learning and to assist complex tasks. Other cognitive support systems that have been, or are being, developed at Sussex include: The Writer's Assistant (Sharples, Goodlet and Pemberton, 1992); MEDICA, a cognitive support system for psychiatry (Smith, 1991); and CORECT, a computer system to assist in the process of capturing customer requirements for the design of automated test equipment.

The original characterisation of a cognitive support system (Sharples and O'Malley, 1988) applies equally to the MR Tutor:

1. The system has a limited teaching strategy: the student directs the activity and the system acts as a 'co-driver'.
2. The system provides support for 'externalising' cognition, showing the student the structure of the problem space, and the steps already taken towards the solution.
3. The system reduces cognitive load by assisting with some of the demanding but lower-level activities [in the case of the MR tutor this includes presenting and windowing the target image, providing rapid access to a database of comparative images, and entering the structured image description through pull-down menus] leaving the learner free to concentrate on higher-level aspects of the task.
4. The system is an adjunct to a familiar activity, performed in a familiar way [an aim of the MR Tutor is to present a student with the task of interpreting an MR image in a manner as close as possible to that of a medical imaging work environment].
5. In order not to increase cognitive load by adding unnecessary representations and operations, the system should be based on the student's perception of the task and should be suited to a range of learners, with different problem solving strategies.

It is most important that the system should match the student's understanding of the task. Task analyses and workplace studies of medical image interpretation and radiology teaching can identify some requirements for an MR Tutor, such as ways to describe images, to select confusable categories of disease and to determine the viewing conditions for the images. However, they need to be supported by a more general theory of interpretation and tutoring of medical images, to ensure that the system design is well-founded and applicable to other contexts.

Visual Concept Tutoring

There are similarities between medical image interpretation and other types of visual concept recognition task. A visual concept is a named mental construct associated with a set of visual images of natural objects, for example cloud formations, crystal structures, or plant diseases. In general, natural categories do not have defining features, but they can be described in terms of a central tendency, or prototype, and variation (Mervis and Rosch, 1981). An instance (a visual image) can be represented in terms of features with associated values (for example "lesion size large"). Natural categories are ill-defined, with fuzzy boundaries, and the instances are not equal: some members of a category (those with a high proportion of feature values which are associated with the category) are more typical than others.

Radiological images differ from conventional photographs of objects in that the visual image is a degraded abstraction of the physical structure. The image quality is greatly influenced by technical factors, and three-dimensional biological structures are usually reduced to modulations of image intensity. For MR images, a radiologist is typically faced with at least two sequences of images each comprising up to 40 slices. The appearance of both normal and abnormal tissues is heavily dependent on the parameter setings at image capture (sequence type) and this adds to the difficulty of image interpretation.

Cognitively Informed System Design

Studies in educational psychology offer a fairly clear and consistent set of guidelines for the teaching of concepts (Stones, 1979; Tennyson and Park, 1980; Novak et al., 1984). Most of these are applicable to computer-based tutoring of MR Images and they have provided a set of general requirements for the first prototype MR Tutor. The remainder of this paper describes the MR Tutor in terms of these guidelines.

Ascertain students' prior knowledge (Stones, 1979)

The MR Tutor is aimed at trainee radiologists who, along with their training in MR image interpretation, are simultaneously acquiring skills in other modalities such as computed tomography, angiography, and plain X-ray. A number of assumptions can be made about the trainees' prior knowledge, for example that they have a basic understanding of neuroanatomy. The system will ask the trainee to make a self-assessment of expertise, in terms of the number of images of a similar pathology that the trainee has already interpreted, and use this to select an appropriate level of sophistication in the image description.

Explain the terms to be used in labelling the concepts and their attributes (Stones, 1979)

The method of structured reporting and the associated MR image description language developed by G. duBoulay in collaboration with De Montfort University provides a comprehensive set of image attributes. The language was developed to enable an expert radiologist to produce an annotated archive of images, and it may need to be simplified for tutoring purposes. A portion of the simplified language, associated with the shape and interior pattern of a lesion, is shown in Figure 1. An independent evaluation of an earlier system for CT imaging (Teather et al., 1988) has identified the training benefits of a structured approach to reporting, linked to a reference set of annotated example images and diagrams.

- Margin
    - Mainly sharp
    - Graded
- Shape
    - Rounded
    - Irregular
        - Area: sq. cm.
    - Conforming to an anatomical feature
- Interior pattern
    - Homogeneous
    - Heterogeneous
    - Containing a distinct focal structure

FIGURE 1. A portion of the Simplified Image Description Language relating to the appearance of a lesion

The image description language is particularly appropriate to computer-based tutoring, since it provides a canonical set of feature descriptors. These are being implemented in the MR Tutor as a frames system in which features are represented by slots whose fillers indicate feature values. The frames form a 'feature space' (Sharples and du Boulay, 1992), where points in the space indicate exemplar images, and regions represent pathologies. Images, pathologies and a student model can be held in a uniform format, which is amenable to statistical measures.

Provide a definition of each concept in terms of its critical attributes (Tennyson and Park, 1980)

Critical attributes are those features that are crucial for categorisation: for example, in recognising birds, colour is likely to be a critical attribute, whereas in categorising vehicles, colour is likely to be non-critical.

The image description language is designed to indicate those features of an image which are crucial to diagnosis. The trainee will indicate the attributes by selecting items from pull-down menus. The Tutor then compares the trainee's selection of attributes with those in the image archive (provided by the expert radiologist) and offers appropriate tuition.

Provide concept maps showing the relationships between concepts (Novak et al., 1983)

We are currently investigating the use of two-dimensional scatter plots to give the trainee an overview of the feature space. The technique of correspondence analysis (Greenacre, 1993) provides a graphical display of complex data. It takes a set of feature descriptors for each case and computes display points (each point corresponding to a case) in two dimensions that represent the greatest variability in the feature space. In order to give an indication of the overall distribution of cases, the space can be scaled so as to indicate the typicality of a case by its distance from the centroid of the scatter plot (Teather et al., 1994). The similarity between any two cases is shown by their closeness in the plot. Thus the correspondence analysis can provide both a visual map of the domain, and measures indicating the typicality of each image and the similarity of cases within a disease.

The graphical overview can assist teaching in a number of ways. The trainee can see at a glance the distribution of cases around a centroid of typicality, and how they form clusters of similarity. As the trainee prepares to select an attribute for the target image, the Tutor can highlight on the overview all those cases that display the attribute, and how they relate to the target. And as part of its broader teaching strategy, the Tutor can indicate on the overview those cases which it judges that the student has successfully completed.

Start by showing a series of simplified exemplar images, with few and obvious attributes, to emphasise the critical attributes (Stones, 1979)

The statistical analysis will provide data on critical attributes, and we are looking at ways of annotating the images to give clear indications of important features such as the shape and extent of lesions.

Arrange the exemplars in order from easy to difficult (Tennyson and Park, 1980)

An important research problem is to determine what constitutes 'easy' and 'difficult' images, and thus to prescribe an optimum order in which the images should be presented for tutoring. For example, should a trainee initially be shown typical images (ones with most feature values in common with others of the category), valid images (ones which are clearly members of the category and not members of competing categories), or salient images (ones with obvious features)? A first step is to operationalise terms such as 'typical', 'similar' and 'cue validity', and we have made progress with this in the context of correspondence analysis (Teather et al., 1994). A further issue is to determine how the order of presentation will be affected after a trainee has chosen to take control and browse through the image set.

Teach coordinate concepts by presenting examples according to their coordinate relations (Tennyson and Park, 1980)

Coordinate concepts are those with similar or overlapping attributes, and can thus be easily confused. The tutoring will be presented in two stages. The first stage is intended to teach trainees to recognise and label features of case images. The second will tutor about pairs of confusable diseases (differential diagnosis).

For the first stage, the MR Tutor draws on the typicality measures and other case information to select suitable cases to present for tutoring. The trainee is shown a target image sequence and attempts to describe it using feature values selected from the image description language. The trainee can call up similar cases for comparison, complete with descriptions, by selecting them from the overview plot.

For the second stage, once the trainee is able to describe cases from individual pathologies, the Tutor shows a target image sequence drawn from pairs of confusable diseases. The trainee is required not only to make an accurate diagnosis, but also to indicate how far, if at all, particular image features support that judgement. Other images from the two coordinate disease categories will be available for reference. The Tutor compares the trainee's judgement of the weight of supporting evidence (whether positive or negative) for goodness of fit with the cumulated weighted evidence derived statistically from cases in the archive.

Provide suitable cueing so that learners gradually become independent in their ability to identify novel exemplars of the concepts (Stones, 1979)

The MR Tutor is designed to provide 'scaffolding' to the trainee in the form of visual cues, overviews and immediate response to actions. As the trainee becomes more proficient in describing images, the scaffolding is gradually withdrawn until the trainee is left with a basic descriptive tool which displays the target image and menus for selecting feature values. At this stage the system will provide a menu-based dialogue similar to the one currently used by the expert radiologist to describe the image archive (du Boulay, 1992).

Implementation

The MR Tutor is currently being implemented using HiPWorks, a multimedia extension to the Poplog programming environment, running under X-Windows on Sun workstations. Figure 2 shows a screen display from the first stage of the Tutor to teach feature recognition and labelling.

The screen is divided into two halves: the right half is for browsing through the image archive and for selecting images to study, and the left half is for tutoring about a selected image. An overview of the feature space of images for a given pathology is shown at the lower right corner of the screen, with a cross marking the centroid, or point of greatest typicality. Each marked point in the overview indicates an image sequence, and clicking on a point loads the images into the viewing area. There are controls to scroll through the slices, alter the image contrast, and save an image in the gallery area.

The trainee selects a case for tutoring, or can allow the system to choose one, according to its teaching agenda. The trainee must then describe the appearance of the image and its abnormalities by picking items from a series of menus that display choices of attribute from the structured image description language. To help in making the selection, as the cursor is moved over a menu item the Tutor indicates cases on the overview that show the attribute. The trainee can call up a case for visual comparison with the target image, and so learns to identify features by visual discrimination of similar cases, as well as by receiving direct tuition.

As the trainee gains in competence, the Tutor will display more detail in the menus, demanding finer discrimination. The response of the Tutor to mistakes will depend on the user's ability, with intervention becoming less frequent and less detailed as the student progresses.

At the time of writing, the overview space and browser are operational, but the tutoring component is still to be implemented.

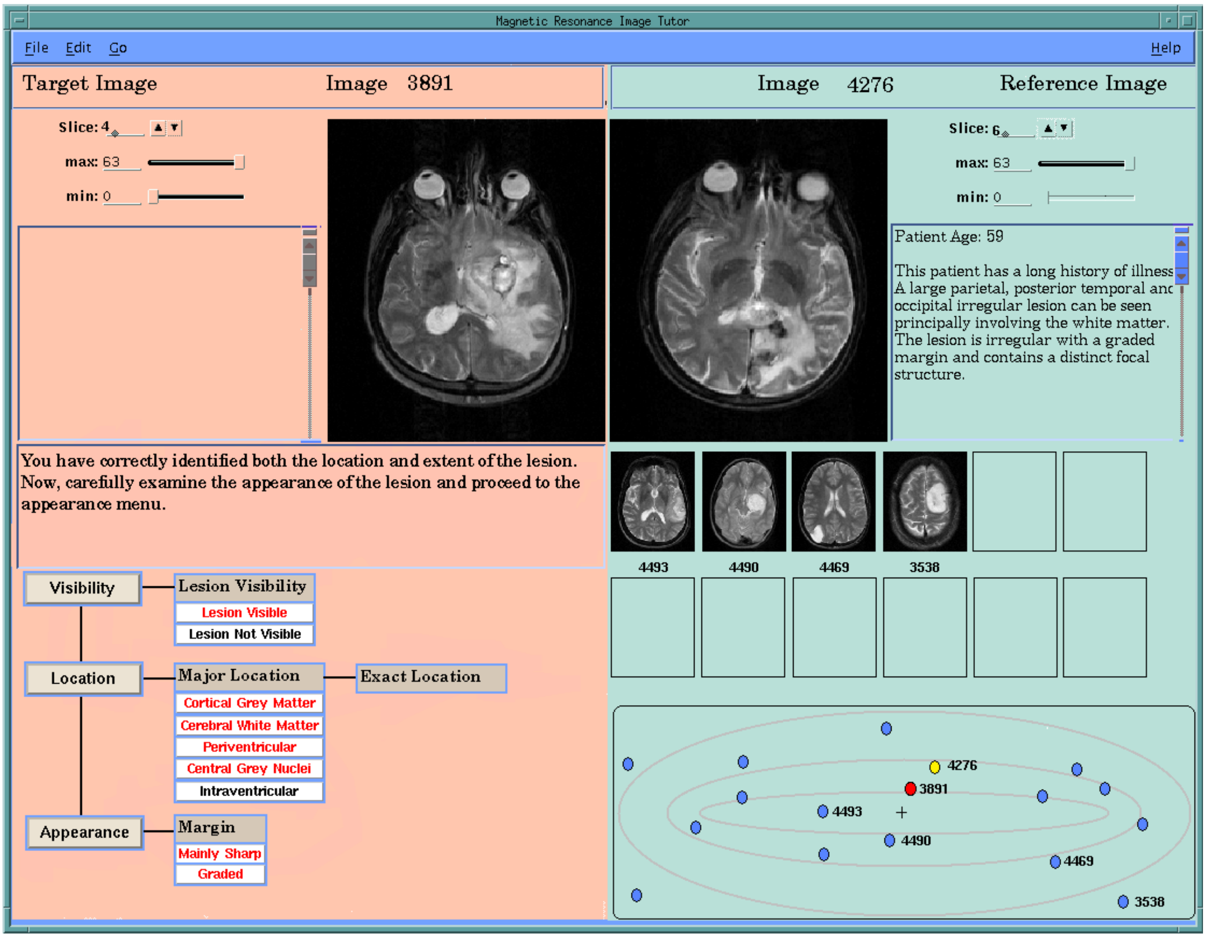

FIGURE 2. A Screen Display of the MR Tutor

Conclusions

Developers of computer-based tutoring systems have paid too little attention to the ways in which cognitive science and educational psychology can inform system design. Our experience is that findings in psychology and cognition, ranging from theories of categorisation to techniques for teaching concepts, can provide explicit guidelines for the design of educational software, that complement the more familiar software engineering approaches such as task analysis and requirements specification. The general approach and set of guidelines described in this paper are not restricted to the tutoring of MR images. They apply more generally to computer-based tutoring of visual concepts, in areas such as geology, botany, and anatomy, and have been used as the basis of a HyperCard program to teach the rules of yacht racing (Dobson, 1990).

The guidelines derived from the literature on concept tutoring are intended only to provide an initial set of requirements for the system. We shall test early prototypes with trainee radiologists at at number of external sites. The intention is to use the series of prototypes to answer the following questions. How can structured reporting, statistical techniques, and the psychology of concept tutoring inform the design of a tutor for medical images? What kinds of tutoring approach are appropriate? Can a computer-based tutor offer a real benefit to radiology teaching?

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