Toward a Theory of Qualitative Visual Reasoning in Microanatomy

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Abstract

Much can be learned about the use of visual information in cognition through the study of visual symbol systems – systems in which a visual structural domain is used to provide information about a target domain (e.g., telescopes used to learn about astronomy). We discuss a recent study that examined a real world task, microscope slide interpretation, in a complex scientific domain, histology. Histology is the microanatomy of biological tissue and consistently depends on the use of microscopes. This investigation demonstrated that identification of histological structures in a microscope is an extremely challenging task with large individual differences. It is remarkable for the degree to which it forces an integration of visual knowledge, generic (anatomical) knowledge, and reasoning into a single cognitive system. These studies point to a development of qualitative reasoning models of recognition, reasoning, and visual analogy in the use of visual symbol systems.

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The authors are engaged in characterizing cognition in the practice of histology, the microanatomy of biological tissue. Histology is a fundamental course in college biology and the medical curriculum. Advanced practice in histology includes the medical discipline of pathology. Of particular interest to our research team, much of histology is practiced with use of a microscope (Crowley, Naus, Steward, & Friedman, 2003). Thus, it is in many ways a paradigmatic case of visual cognition.

In this paper, we describe cognition in histology as a type of information system and as a type of world domain with its own constraints. We attempt to lay out the basics of an analytical approach to histology that ultimately can yield a detailed model of qualitative reasoning in this area (Bredeweg & Struss, 2003; Forbus, 1983; Weld & de Kleer, 1990). Our own emphasis is on simulation of human behavior as a means for guiding improvements in instruction. However, most of our discussion would be equally useful for those interested in building autonomous artificial systems for the interpretation of visual information.

Our current understanding of histology is based on discussions among the authors, who include cognitive scientists and a biologist and instructor in histology, and on two interview studies with college students. The first interview included five recent graduates of the college course in histology. The second interview included eight students who were then enrolled in the course. In all cases, participants viewed tissues in a microscope and attempted to identify them. A variety of verbal protocol (think aloud) and structured interview techniques were used to elicit information from the students. A video camera recorded the view through the microscope and all verbal exchanges.

Visual Symbol Systems

The consistent use of the microscope in histology places it in the class of human activities that involve a symbol system. In particular, there is a domain of objects – the information domain – that is used to provide information about a second domain – the target domain. In this case, microscope slides provide information about microanatomy. Histology is a visual symbol system, and it is part of a class of visualization systems that have been developed in science, engineering, and medicine, including the areas of astronomy (e.g., telescope views), radiology (x-ray, CT, MRI), aerial photography, seismology, radar, and so on (see, e.g., Brooks, Norman, & Allen, 1991; Hoffman, 1987; Lesgold, 1988). Although these are visual symbol systems, verbal description is typically an important part of their use. Hence, visual symbol systems ultimately include three domains of importance: the visual information domain, the target domain, and the linguistic domain.

Mapping Between Domains

The nature of the mapping between target and symbol is crucial in any symbol system. What is the useful structure of the target domain? In this case, how do people describe microanatomy, and what do they want to know about it in individual cases? What is the useful structure of the information domain? Here, what is the structure in microscope slides that provides information about microanatomy? Where is the mapping between domains one-to-many, generating categories of symbols, all of which mean the same thing? Where is it many-to-one, generating ambiguity of symbols? Where is it one-to-one, providing high-fidelity information? Are there

qualitative properties of the mapping between domains that make information more or less efficient to use?

It is crucial in pursuing such questions to respect the distinction between the objective nature of the mapping – the potential information that a person could use – and the psychological or cognitive nature of the mapping – the information that the person has actually picked up or is capable of using. The distinction is especially important for scientific and medical symbol systems, for they tend to be confined to particular contexts and to be learned later in life (i.e., in college or in professional training). Unlike language, histology only takes place when someone looks at microscope images, and it is only taken seriously in college or medical school. Thus, the development of expertise in the use of information in histology takes many years (Crowley et al., 2003).

The Domains in Histology

Target Domain -- Anatomy. The target domain in histology covers the primary types of cell (e.g., nerve, gland, fat, and muscle), the basic tissues (e.g., connective tissue, muscle, and the epithelia), and their arrangements in the organs and basic structures of the body (e.g., skin, lung, pancreas, and liver). The primary organizational scheme is a hierarchical composition of the whole body, with uniform levels of parts composed of lower levels of parts. Thus, organ systems (e.g., urinary) are formed of organs (e.g., kidney), which are formed of structures (e.g., glomerular capsules), and so on, through the level of cell organelles and down to the level of molecules. There is also a well formed taxonomy that relates types of cell (e.g., nerve and gland) and correlated tissue types (nerve tissue, glandular tissue, and various types of glands).

Information Domain – Microscope Slides. The mapping in histology from target domain to information domain stems from the formation of microscope slides. As illustrated with the sweat gland in Figure 1, the various cells, tissues, structures, and organs that form the human body are three-dimensional. Viewing them under a microscope involves treating them with a preservative, staining them with one of a number of color schemes, and then sampling thin planar sections from the treated tissue. The slides may include substantial portions of organs, and they provide good visual resolution down to the level of cell membranes and nuclei.

A primary challenge in the use of microscope slides is that three-dimensional structures in the tissue must be identified using essentially two-dimensional samples of them. In addition, these two-dimensional samples are sections through the interior of the structures. We normally recognize three-dimensional objects easily, but this generally involves looking at the whole objects from the outside. Two dimensional slices through the interior of a structure typically do not preserve the structure and appearance of the whole. A third difficulty

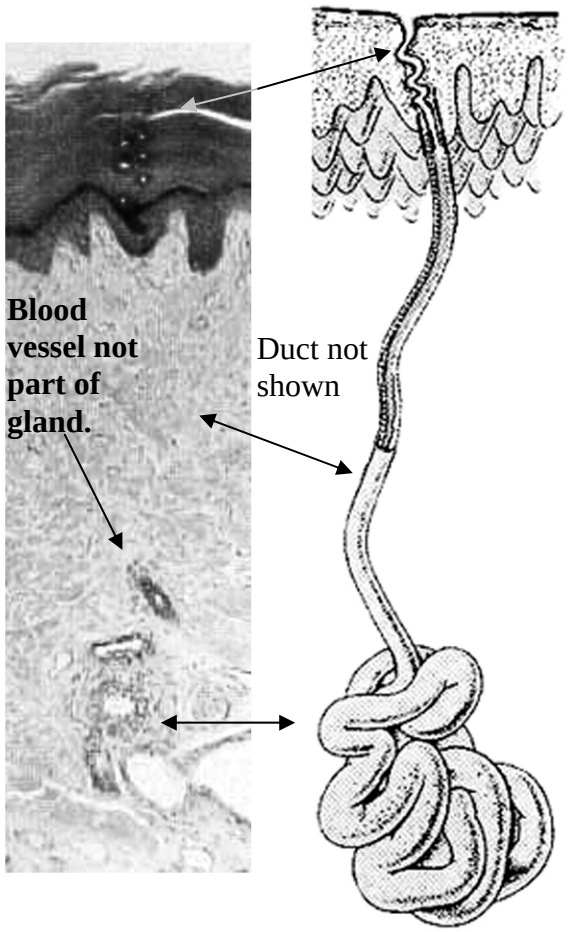

Figure 1. A sweatgland and its representation in a microscope slide.

for recognition in a microscope is that different staining methods result in slides for a single tissue that can look very different. Substructures may disappear or become highly salient, depending on the stain that is used. Fourth, two-dimensional tissue sections can be taken at different orientations to the three-dimensional structures. The result is that the same three-dimensional structure can have many different two-dimensional views. For example, when a tube is cut in cross-section, it has a circular shape. When the same tube is sectioned obliquely, it will have an oval shape. A longitudinal section will result in a long rectangular shape. Fifth, variation of shape in the tissue itself, as well as the position of the slice, determines that substructures may or may not appear in a particular sample taken from a structure. Lastly, structures that are quite different anatomically can look quite similar in microscope slides due to the changes in structure that result from the slice transformation.

Summary of the Mapping in Histology. The overall situation may be summarized with four points. 1) Histology includes a visual information domain and an anatomical target domain that are both very large and complex. 2) The target and information domains are related by a spatial transformation (taking thin slices) that

does not generally preserve appearance. 3) There is a one-to-many mapping from the target domain to the information domain. A single type of structure can have a wide variety of looks in a microscope. 4) There is a many-to-one mapping from the target domain to the information domain. Different structures often look alike.

Evidence from the first Interview Study

Participants

This situation presents a substantial challenge for the use of information in microscope slides. Consider the performance of five individuals in the first interview study. All students had completed the undergraduate course in histology within the previous year. They were all juniors or seniors in the pre-medical or pre-dental college curriculum. Four of the students had received a grade of A in the course and one had received a grade of B.

Materials and Procedure

The participants were interviewed separately. Four different slides were viewed through a binocular laboratory microscope. There was first a verbal protocol for all four slides. During the protocol, participants were to "think aloud" as they viewed the slide. They were assured that they were not being tested; instead, the objective was to understand the natural process of slide reading. They were encouraged to change focus and magnification as needed, and to follow their own pace. After the verbal protocols were completed, structured interviews took place. Two interviewers reviewed a checklist of structures for each slide and agreed on the structures to be reviewed. Each slide was viewed under the microscope a second time. The majority of the questions in the structured interview referred to structures that had been omitted or misidentified earlier. The participants were given a second chance to identify and to discuss the whole tissue.

The four slides differed along a number of dimensions. A slide from the scalp was expected to be an easy slide for the students to identify and describe. The scalp is complex, with numerous intermingled structures. However, it contains several salient diagnostic structures (e.g., hair follicles). It was a tissue that the students had all seen and studied in class, and the stain that was used on this particular slide was familiar to the students.

The tendon was a simple tissue that all the students had studied, and the stain was a familiar one. However, it was expected to be somewhat challenging for two reasons. First, distinguishing the tendon from similar tissues requires judging the arrangement of cell nuclei rather than the presence or absence of particular structures. Second, the collagen fibers that often can be seen in a tendon were not easy to discriminate in this slide.

The pancreas was a tissue that the students were familiar with, but the stain on this slide was one with which the students were unfamiliar. The slide was moderately complex because there were several structures to identify. A correct identification of the pancreas depended on the identification of a single diagnostic structure, the islets of Langerhans.

The epiglottis was a tissue that the students studied but had not seen in a slide. The slide contained many structures common in other parts of the body, and the stain was one that was familiar to the students. Correct identification required knowing a configuration of structures (i.e., epithelial layer, salivary glands, and elastic cartilage) rather than one unique diagnostic characteristic. In the following brief discussion, we organize the summary of results in terms of important implications for modeling human performance.

Basic Results and Implications

Level of difficulty. Microscope identification is clearly challenging. The average time the participants spent identifying and describing the slides in the verbal protocol ranged from close to 3 minutes for the tendon (the simplest tissue) to almost 7 minutes for the epiglottis. Participants used all three magnifications to view the tissues and changed magnification frequently. The time spent during the verbal protocol attempting to identify the tissues is presented in Figure 2. Note that the scale is in minutes.

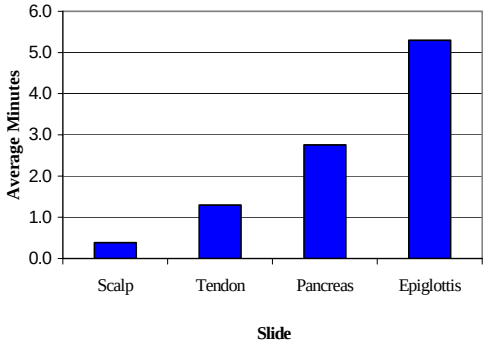

Figure 2. Time attempting to identify each tissue.

With five students looking at four slides, a correct identification of the whole tissue was made 12 times during the verbal protocol out of the possible 20 identifications. There was substantial variation among the difficulty of the tissues and among the performance of the participants. All five participants were able to identify the slide of the scalp at least to the level of thin skin. Four of the five participants identified the tendon. For the pancreas and epiglottis, fewer participants identified the slides correctly. Two out of five participants identified the pancreas, and the identifications required an average

of two minutes. Only one participant out of the five was able to identify the epiglottis in the verbal protocol. This participant made the identification in 33 seconds. One additional participant identified the epiglottis after extensive reasoning in the structured interview that was based on the combination of tissue shape and the structures on the slide.

Participants missed the identification of individual structures on the slides in a number of ways. Misidentifications often involved confusions that could only occur due to the slice transformation. For example, sebaceous glands in the scalp are globular structures formed of cells filled with fluid. They were twice confused with nerves cut in cross-section and once confused with muscle cut in cross-section. Such misidentifications always involved confusing a less common structure with a more common one.

Visual Discrimination. One type of challenge for the participants clearly was visual discrimination of structures in the slides. There were structures that the participants expected to see but could not find on the slide, and there were structures that the participants appeared not to notice. When these structures were cued in the structured interviews, they typically were correctly identified. In one case a highly diagnostic structure had been missed, and the whole tissue was correctly identified after the structure was cued by the experimenter.

During the structured interview, one of the participants retracted a correct identification of the pancreas made during the verbal protocol. This participant could not confidently identify a structure on the slide (i.e., islets of Langerhans) that would differentiate between pancreas and kidney. This was an interesting case in which the participant clearly enunciated how the decision could be made but could not make up her mind about what she was seeing in the slide. In a similar case with the same diagnostic structure, a participant explicitly rejected its correct identity. This slide included a stain of the pancreas that the participants were not used to seeing

Categorical Recognition. A participant could identify a structure at a general categorical level (e.g., pancreatic alveoli could be called "glandular") or at a specific categorical level (alveoli). One interesting outcome in this study was the frequent recognition of tissues at a relatively high categorical level. It was common for participants to quickly label a variety of glands as "glandular", even though they come in a variety of distinctive types. Similarly, participants would often identify "cartilage", even though the identification of elastic cartilage is an important histological distinction. The proportion of structures correctly identified at the general and specific categorical levels for each slide is presented in Figure 3.

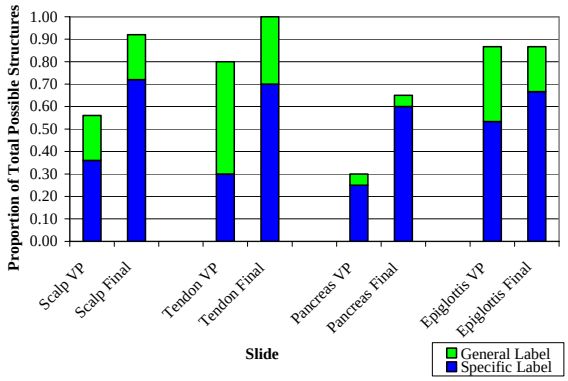

Figure 3. Proportion of categorically specific and general terms used during the verbal protocol and overall for each tissue.

Reliance on Reasoning. The very challenging nature of microscope identification in histology is quite familiar to the students, and it became clear that a variety of forms of reasoning are employed to manage the situation. The following excerpt is representative:

It looks kind of like a tendon.
I don't know if I just don't have the focus right or maybe I don't have the iris right
but you can usually see wavy things on tendons.
But all the nuclei are kind of in lines.
They are sort of orderly.
Which is usually the way tendons do. [high magnification]
But you can usually see the collagen in them better though.
So, that's kind of weird…
But I don't think its smooth muscle.
Because that's the only thing that tendons are real easy to
Oops there you go you can see it better now.
Not quite like it's supposed to be but that's ok.
But like tendons have their nuclei are longer.
And they're more organized.
And smooth muscle has long nuclei
but they are all in crazy patterns.
And these are sort of organized.

All of the methods that participants used to work toward an identification are listed in Figure 4. The frequency of use of each method is presented in Figure 5. It is clear from that graph that it was relatively common for participants to recognize individual structures and then immediately infer the whole tissue. It is equally clear, however, that a variety of hypothesis testing methods were used. Of particular interest, there was no confirmation bias (compare Klayman & Ha, 1987). To the contrary, these students have developed skill in an area in which it is important to be sensitive to disconfirming information.

Attempts at Recognition
Immediate recognition of whole tissue
Recognition of one or more parts; Immediate inference of whole tissue
Recognition of one or more parts; Immediate inference of high-level category
List a set of features; infer a structural form
List one or more parts; Search memory for matching description
List one or more parts; No further action

Hypothesis Testing
Generate Hypothesis: Confirm: Find structures consistent with hypothesis
Generate Hypothesis: Confirm: Search for inconsistent features
Generate Hypothesis: Disconfirm: Absence of consistent structure
Generate Hypothesis: Disconfirm: Presence of inconsistent structure
Use confirmation/disconfirmation to weigh two alternatives

Post-hoc Justification
Post hoc justification: Confirm: Presence of consistent structure
Post hoc justification: Disconfirm: Presence of inconsistent structure

Figure 4. Master List of Cognitive Processes Used in Tissue Identification

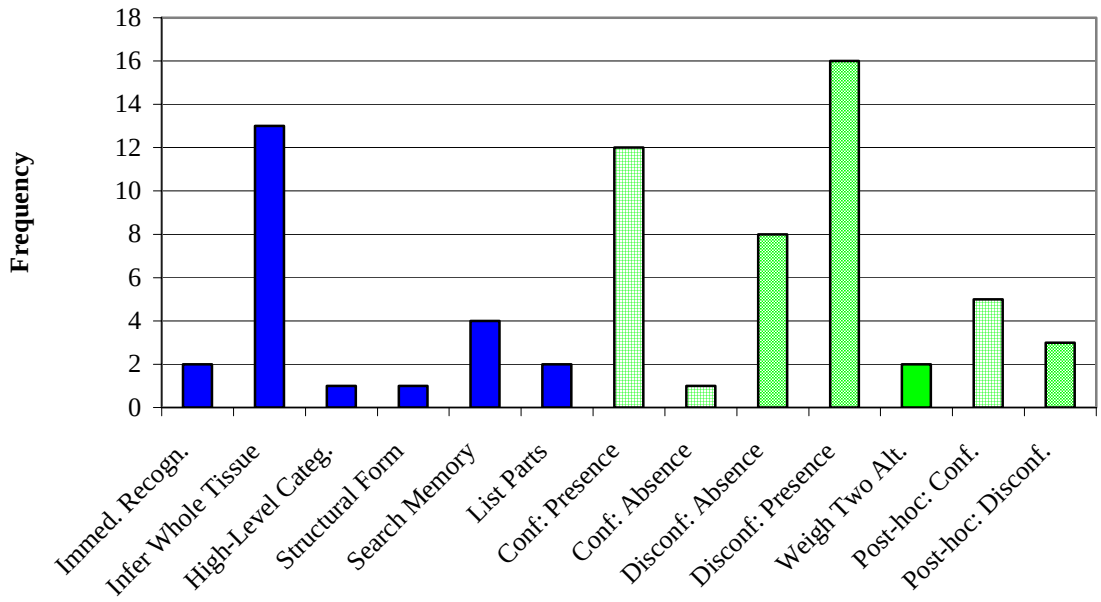

Figure 5. Frequencies of Cognitive Processes Used in Tissue Identification

Toward a Model of Cognition in Histology

The investigation of cognition in histology has generated substantial information that can guide building a model of its operation. Among the many modeling tools available, concepts from the study of Qualitative Reasoning will be quite useful. In the remainder of this discussion, we focus on issues related to qualitative reasoning.

Mental models. Budding histologists inherit a detailed model of the hierarchical composition of biological tissue. It is a discrete and categorical model. Cutting across this compositional hierarchy is a taxonomy of tissue and cell types. Both of these models are consistently expressed in the language in which histology is taught and practiced, in the recognition and examination of microscope slides, and in remembering and reasoning about anatomy as it is related to the interpretation of slides. Simulation techniques that provide representation and use of discrete, hierarchical, and categorical models are necessary to simulating cognition in histology.

Object Recognition. Most microscope slides appear complex and nonsensical to the untrained eye. With experience in histology, however, they became immediately meaningful in terms of their relations to the mental models of anatomy (and can never again be seen as unmeaningful). "This is skin. This has got to be a tendon. This appears to be glandular." are confident assertions that become commonplace in the study of histology. The translation of visual information into high level categorical objects has been called Qualitative Spatial Reasoning (Bailey-Kellogg & Zhao, 2003). It is a discipline that seeks, for example, to identify weather fronts, tornadoes, and hurricanes from the low level data of distributed weather stations. Picking out a hair follicle from a microscope preparation of thin skin may prove to be a task that is similar in many ways.

Reasoning. Cognition through a microscope always begins with some instance of recognition. Quite often the recognition in histology occurs at a relatively low level of structure, and inference of the whole tissue must take place. In many instances, initial recognition leads to more than one possible interpretation, and reasoning must be used to narrow down the identification. Quite often this leads to further exploration of the slide. This may be specifically targeted (e.g., if this is a kidney, I should be able to find proximal tubules) or it may be more exploratory (let me see what else is around here). In both cases, practitioners must be adept at using both confirmatory and disconfirmatory information and at integrating information to build a case for and against alternative identifications. Simulating this cognition will require models that guide exploration, visual discrimination, object recognition, and the integration and weighing of evidence in the pursuit of the goal of identification with respect to histological categories.

Visual Analogy. Any domain of visual recognition possesses its unique assets and challenges. In the visual symbol system of microscopy in histology, these stem from the role of the slice transformation in relating the information domain to the target domain. We have pointed out the challenge for recognition that is presented by this transformation. However, we believe that there also are very substantial benefits relative to other possible mappings between information and target domains. That is because the slice transformation leaves many instances of topology and categorical spatial properties invariant. Substantial amounts of *Visual Analogy* are available, and the histologist can learn to use this information to guide recognition and inference.

Examples of abstract properties that are quite often invariant between microanatomy and a microscope slide include the presence of large boundaries, containment, density, number, curvature (spheres become circles), regularity (e.g., parallelism), and a number of fundamental categories of shape, such as nodular, fibrous, and layered. Variation among tissues and the geometry of the slices determine that the invariance is not perfectly uniform. Most probably there are canonical and noncanonical slide views for any of these properties and for the anatomy that is evident through consideration of them.

Sensitivity to visual analogy among the slides helps to account for two further findings that emerged in the interviews. First, in open-ended discussions about mental representation, three out of four participants who were given a series of options to consider said that when they looked at a slide they felt as if the whole tissue were there (i.e., not just a slice from it). They were not inclined to attribute this to mental imagery. It was more like having a single point of view on a scene and knowing that other views would reveal other visual structures. Second, explanations of how something was recognized often appealed to semantic knowledge about the whole tissue. Glands were said to "look full" and as though they were "getting ready to squeeze out their juices".

Visual analogy is a type of mapping between domains that allows relatively efficient learning and inference of the informative relationships between slides and anatomy. Modeling the use of such structure in visual symbol systems may be a valuable exercise in qualitative modeling.

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