Visual Cognition in Microscopy

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Abstract

We can learn a great deal about cognition through the study of visual information systems – systems in which a domain of visual information is used to explore a separate target domain (e.g., telescope images used to explore astronomy). This study examined a real world task, microscope slide interpretation, in a complex visual domain, histology. Histology is a fundamental course in biology and medicine, and it is central to the practice of pathology. This investigation demonstrated that identification of histological structures in a microscope is a challenging task with large individual differences. It is remarkable for the degree to which it encourages an integration of visual knowledge, high level recognition, general (anatomical) knowledge, and reasoning into a single cognitive skill.

Keywords: visual cognition; expertise; microscopy; perception; reasoning; scientific reasoning; education; skill.

Microscopy as a Visual Information System

Disciplines that seek to maximize human expertise seem generally to employ visual information systems. A visual information system, as we will use the term, includes a domain of visual structure that is constructed purposely to provide information about a target domain. Very often the target domain in a visual information system is inaccessible to observation except through the information domain. Thus, the discipline of astronomy depends on telescopes to provide information about extra-terrestrial objects, a physician uses EKG to examine a living heart, air traffic controllers use radar images to visualize extended traffic patterns, and neuroscientists use MRI to study the intact brain (e.g., Brooks, Norman, & Allen, 1991; Hoffman, 1984; Lesgold et al., 1988). Study of the learning and use of visual information systems provides a number of opportunities to gain insight into fundamental properties of cognition. These insights can be used to aid the development of training techniques in the various disciplines that depend on visual information systems.

We report here two studies aimed at understanding the use of microscopy in histology. Histology is the microanatomy of biological tissue (e.g., Ross, Kaye, & Pawlina, 2003). It is a core course in both the biological and medical curricula, and it is essential to the study and practice of pathology. The discipline of histology depends on the use of microscopes. Knowledge of highly complex three-dimensional tissues is obtained by viewing, at high magnification, thin slices that have been removed from the tissue, chemically fixed, and stained to emphasize a variety of structures.

Microanatomy concerns 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). Students learn microanatomy from textbooks, a few diagrams, and illustrative photographs of microscope slides related to the text and diagrams. At least half of course time (and much more than half of study time) is devoted to learning to recognize these structures in microscope slides. This central role for the microscope continues into the practice of pathology (Crowley, Naus, Steward, & Friedman, 2003).

The Challenge of Microscopy in Histology

The challenge in interpreting microscope slides depends in large part on the nature of the mapping between the target domain and the information domain in this discipline. First, as illustrated with the sweat gland in Figure 1, the structure of the visual patterns seen in microscope slides is generally not the same as the structure of the whole tissue. The organs and tissues that form the human body are three-dimensional, but they must be identified in the microscope with essentially two-dimensional sections from their interiors.

A second challenge in microscopy it that the mapping from target domain to information domain is both many-to-one and one-to-many. Structures that are quite different can appear to be very similar when a thin slice through them is the only information about them that is available. Moreover, many different organs and systems in the anatomy of an organism can include the same individual types of structure (e.g., ducts or layers of epithelium). On the other hand, the same structure can appear in many different ways in a microscope slide. Different staining methods can result in different appearances. Tissue sections can be taken at different orientations to the three-dimensional structures, resulting in a variety of two-dimensional views. Finally, the position of a section from a tissue may determine whether a particular structure in the tissue does or does not appear in the slide.

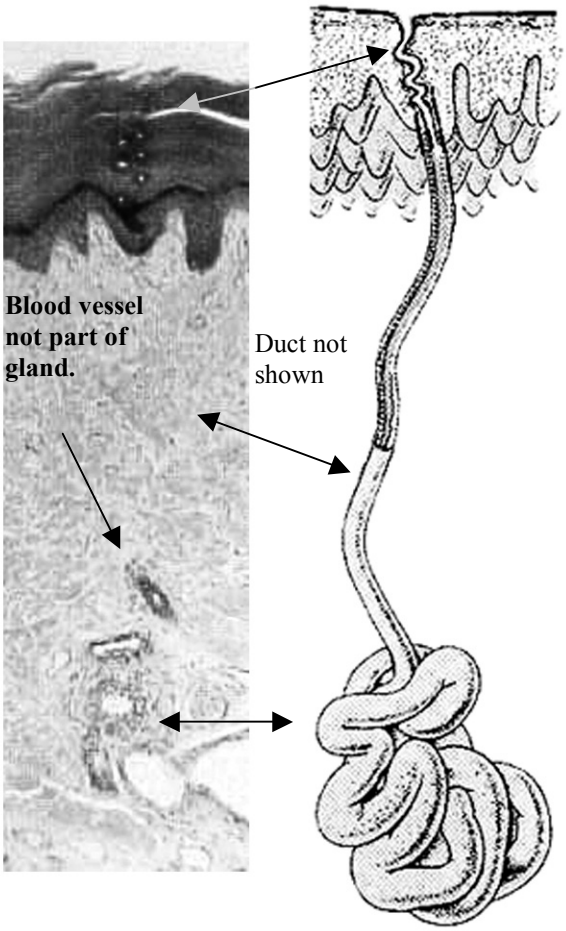

Figure 1. A Sweat Gland and a Section Through It

Research Method

So little is known about cognition in microscopy that our work has begun with two interview studies (see Ericsson & Simon, 1993) with students in the basic undergraduate course in histology. The intent was to observe a variety of phenomena that, at a cost of statistical power, would indicate the nature of the skill as a whole. For a related study that looked at the development of expertise in pathology, see Crowley et al. (2003).

Participants in our studies viewed microscope slides through one head of a two-headed laboratory microscope. A video camera was aimed through the other head of the microscope and recorded what the participants saw and the manner in which they explored the slide. A microphone attached to the video camera recorded everything that the interviewers and the participants said.

These studies were rich sources of information in the form of first hand observation of practice and visual and auditory recordings of verbal protocols, structured interviews, and open-ended discussions. So as not to become lost in a sea of data, we begin by presenting the fundamental components of a model that has emerged from the two studies. We then describe the studies, relating the data to the model.

A Model of Cognition in Histology

The development of expertise in histology takes place in two streams of experience and cognitive representation. One stream concerns the microscope slides (the information domain) and the other concerns anatomy and physiology (the target domain). These streams increasingly develop into one interconnected knowledge structure with multiple modes of representation (see van Someren, et al., 1989). The existence of relatively abstract structural invariants across the slide and anatomical domains is an important aid to this integration. For example, in both an actual pancreas and in a microscope slide from a pancreas, one finds an interlobular duct and cuboidal epithelium, and the duct is lined with the epithelium.

Histological practice includes microscope slides that must be visually perceived and recognized. Efficiency demands that the value of visual information is maximized. That is, what visual recognition can provide, recall and reasoning need not. On the other hand, the challenges presented by the mapping between slides and anatomy in histology determines that visual recognition is not always successful. When it is not, recall and reasoning are important for identification.

Within the slide domain, practitioners face several constraints and develop several types of skill (for related discussion, see Oliva & Schyns, 1997; Schyns, Goldstone, & Thibault, 1998). One critical skill is a relatively low level ability to visually organize and recognize information, as takes place in normal face perception. Tissues come to have a characteristic "look". In addition, expertise develops for categorical encodings of visual episodes (one's lab mate's pancreas slide) and prototypic visual configurations (what most pancreas slides have). These representations include multiple levels of hierarchical composition, and they can be quite complex. The representations are also well integrated with the verbal knowledge that applies to the whole anatomy. Histologists must be able to talk about what they see. The development of expertise in the slide domain is carefully guided (and tested) by the curriculum. All good students learn to "see" loose connective tissue and to recognize prototypic cases of "gland".

Biological tissue is complex, and histology is an exact science. Recognition of a slide requires that all structures in the slide fit the proposed anatomical concept, and that no structure known to be in the anatomical concept is inconsistent with the structures in the slide. In the general case, then, identification of a tissue requires model-based recognition that integrates recognition of individual structures into a single scene-based interpretation of the tissue as a whole.

In practice, recognition of parts of a tissue does not ensure that the whole tissue is immediately or confidently identified. In such cases, perception gives way to an integrated process of perception and thinking. This generally takes the form of hypothesis testing, and it can be implemented either with knowledge encoded through

experience in the slide domain or with knowledge of anatomy and physiology. In the slide domain, the practitioner can review the possible interpretations of the tissue based on knowledge of how tissues look in slides. In the anatomical domain, the practitioner can attempt to develop a plausible anatomical interpretation of what gave rise to the slide. Such reasoning is sometimes spatial in character and on occasion includes hand gestures.

With reasoning, visual perception of the slide becomes incorporated into goal-directed search for structures and evaluation of their consistency with hypotheses. In these cases, practitioners clearly are using diagnostic information about tissue. Quite often they look for visual features that are not at all salient to the untrained perceiver. Interestingly, what is learned as diagnostic in the context of a college course can underestimate the diagnostic information available in histology.

Whether a microscopist will reason in the slide domain or the anatomical domain depends on the value of visual information in leading to an identification of the tissue. In numerous cases, visual information is insufficient or even misleading, and the more successful practitioners are able to introduce anatomical knowledge in a way that augments or reinterprets the initial response to the visual information.

The overall cognitive system in histology is a seamless integration of trained visual organization, high level recognition, and reasoning in both the slide and anatomical domains. The integration is aided both by the common language used for slides and anatomy and by the abstract spatial invariants that span them.

Practitioners come to ignore the difference between recognizing a slide and seeing an instance of anatomy. The slide is a viewpoint on the anatomy, much as one recognizes an object that is partially occluded. Successful processes of reasoning lead to model-based recognition of the slide, so that immediate recognition and reasoning-driven interpretation are not clearly differentiated.

Interviews with Students from the First Year Course in Undergraduate Histology

Participants

In Study 1, five undergraduate students, three females and two males, participated in two sessions, each lasting approximately one and one-half hours. All students were in the pre-medical or pre-dental curricula. Four of the students had received a grade of A in the course and one had received a grade of B. All students had completed the undergraduate course in histology within the previous year.

In Study 2, participants were eight students enrolled in the histology course. Six were female and two were male. Four of the students had received a grade of A on the first exam, 1 had received a grade of B, and 3 had received a grade of C.

Method

Materials. In Study 1, four histological slides were viewed through one head of a two-headed laboratory microscope. A slide from the scalp was expected to be easy 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 studied in class, and the stain in this particular slide was familiar to the students.

A section from a 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 to identify, because the collagen fibers that often can be seen in a tendon were not easy to discriminate in this slide.

A slide of the pancreas showed 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, with several structures to identify.

The epiglottis was a complex 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 rather than a single diagnostic characteristic.

Study 2 featured a comparison between tissues presented in familiar and unfamiliar stains. Participants first saw the unfamiliar stain of the pancreas presented in Study 1. That was followed by an unfamiliar stain of the lung. The relatively easy slide of the scalp then was presented. The last two slides were stain preparations of the pancreas and lung that were familiar from the histology lab.

Procedure. In Study 1, the first session consisted of a verbal protocol followed by a structured interview. For the verbal protocol, participants verbalized their thoughts as they viewed the four slides under the microscope. Participants were asked to "think aloud" as they viewed each 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 protocol was completed for all four slides, the structured interview took place. The 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, and a series of questions was asked. The majority of questions referred to structures that had been omitted or misidentified earlier.

In Study 2, the verbal protocol and structured interview were combined into a single method. Participants were encouraged to speak freely. However, identifications were followed by questions about how the participant had decided on the identification. Omitted structures were queried in the same session. Failures at identification were followed up with requests for best guesses.

Results

The importance of visual recognition. In Study 1, the mean time that the participants spent identifying and describing a tissue ranged from 3 to 7 minutes across the four slides. The mean time prior to identification of the whole tissue, or to a decision to give up trying, correlated closely with the expected level of difficulty. These times ranged from less than 30 seconds for the scalp to over 5 minutes for the epiglottis. Participants used all available magnifications to view the tissues and changed magnification frequently.

A correct identification of whole tissue was made 12 times during the verbal protocol out of the possible 20 identifications (five students looking at four slides). All five participants identified the scalp. Four identified the tendon. Two participants identified the pancreas in the unfamiliar stain. Only one participant was able to identify the epiglottis during the verbal protocol.

This variation across the four slides clearly implicated the importance for tissue identification of familiar visual information. The scalp included salient diagnostic features in a familiar stain, the tendon was a simple structure in a familiar stain but included an unclear presentation of an important feature (collagen fibers). The pancreas was presented in an unfamiliar stain, and the epiglottis had not been seen in a slide before.

The importance of familiar visual information was reinforced in Study 2 by the comparison of identification for familiar and unfamiliar stain preparations of the same tissues. Two participants (out of eight) identified the unfamiliar pancreas without prompting about specific structures, and 1 participant identified the unfamiliar lung. In contrast, 5 participants identified the familiar pancreas without prompting, and all 8 participants identified the familiar lung easily.

Categorical recognition. Tissues were quite often described at a relatively high taxonomic level. For example, it was common for participants to quickly label glands as "glandular" or to refer to a blood vessel without regard to whether it was an artery, vein, or other type of vessel. Categorical recognition was most apparent in the identification of individual structures within the whole tissue. The proportion of structures correctly identified at general and specific levels for each slide is presented in Figure 2. Note that recognition at high taxonomic levels is often not the best use of information for purposes of identification (i.e., it can be too general).

Discourse about the slides. Coding of student discourse began with a preparation of written transcripts and a conversion of these to individual statements. These corresponded to simple but complete thoughts. For example:

Because that part is skin.
Yeah, that part's skin…
With its little layers that come apart.
It gives you dandruff, too.
Which is weird that I remember that.
But it's thin skin.
Because the part that can peel off is relatively thin.
Like if you look at it it contrasts with the palms of your hand.
Where that stratum corneum layer is really thick.

In a coding system developed for the verbal protocol of Study 1, the participants' language was expressed in terms of a minimal set of propositions (elementary relational statements and their arguments). A system of 38 propositions accounted for all statements across the five participants. Nearly sixty percent of all propositions used by the participants referred to structures on the slide. For example, three percent of propositions asserted that a structure looked like a given type of structure (LOOKSLIKE[X,Y]). Fourteen percent of propositions were associated with reasoning. For example, a little over two percent of propositions involved contrasting new information with previous information (CONTRAST). Almost sixteen percent of propositions were expressions of prior knowledge. For example, ten percent of propositions were noun phrases referring to histological categories.

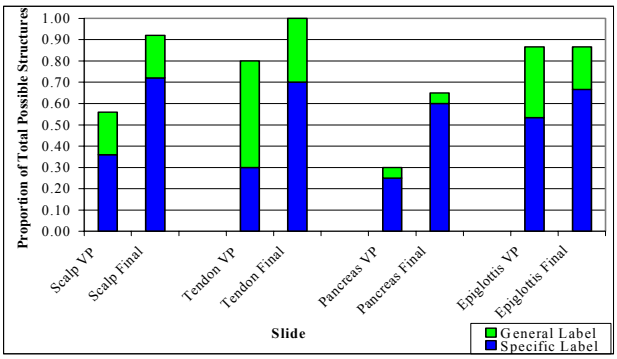

Figure 2. Proportions of Specific and Categorical Identifications of Structures in Study 1.

Participants' language almost never differentiated between the structure in a microscope slide and the structure of whole anatomy. In those cases where this clearly might have been done, language for a structure that had been identified referred to the whole tissue. For the convoluted tubule at the bottom of Figure 1, for example, a typical description would refer to "this duct" rather than to "these bits of duct."

A second coding system was developed to capture goal-directed cognitive processes. A master list was composed of the types of elementary cognitive process used to work toward the goal of identification. The list is presented in Figure 3. For each participant and each slide, progress toward identification was then diagrammed using the listed processes in the order in which they occurred.

The frequencies of the individual types of cognitive process are presented in Figure 4 for the verbal protocol in Study 1. The 13 types of cognitive process were divided into three categories: attempts at recognition, hypothesis testing, and post-hoc justification. By far the

most prevalent form of recognition was noting structures on the slide and then immediately inferring a whole tissue. This clearly depended, however, on the nature of the tissue and the slide. The scalp, indeed, was invariably recognized from hair follicles or the characteristic epithelial layers in thin skin. In Study 2, however, the most common response to the familiar lung was immediate recognition of the whole tissue (7 out of 8 participants). As one student said, "Nothing else looks like that."

There were 39 instances of hypothesis testing in Study 1. Of these, there were 13 times when participants considered confirming evidence and 24 times when participants considered disconfirming evidence. There appears to be no confirmation bias in histology. On the contrary, students were painfully aware that they might be wrong in their conclusions.

Incorporation of reasoning. Reasoning about the tissues took a variety of specific forms, but in general it involved an evaluation of evidence concerning a hypothesis. In every instance, the advent of reasoning could be traced to a problem in using visual information to obtain a confident interpretation of the whole tissue. In the case of the tendon, reasoning clearly focused on the visual features of the tissue as it was manifested in the slide:

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.

Those students who were able to identify the tissues that the majority of students could not accomplished this through reasoning that incorporated anatomical knowledge. This knowledge allowed transcending the limitations of the immediate visual information. These limits were apparent, for example, in the case of the pancreas presented in the unfamiliar stain. The islets of Langerhans is a structure in the pancreas that is highly diagnostic. In Study 1, two students did not notice the islets and one otherwise very skilled student noticed them and explicitly rejected them as islets of Langerhans. In contrast, one of the students who did identify the pancreas considered the slide to be equally representative of pancreas and kidney, two tissues that do not look very much alike. This student enunciated lists of diagnostic features for both pancreas and kidney but had difficulty matching them to the visual structures in the slide. A lengthy process of hypothesis testing generated the correct answer.

The one student in Study 1 who easily identified all of the tissues had clear and extensive anatomical descriptions that were used to interpret the slides. When this student was asked at the end of the study how he learned new tissues, he said that he began by mastering the anatomy of the whole tissue through the descriptions in the textbook. After that, he went to the microscope and looked for the structures that he knew should be there.

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 3. Master List of Cognitive Processes Used in Goal-Directed Cognition

Discussion

In histology, there are differences in structure between what is visible in microscope slides and what is known about the whole tissue. Moreover, the mapping from tissue to slides is many-to-one and one-to-many. As a consequence, identification of biological tissue in a microscope is often challenging, and individual differences among student practitioners are large.

Successful identification of histological structures in a microscope is remarkable for the degree to which it depends on an integration of visual knowledge, high-level recognition, general (anatomical) knowledge, and reasoning. As expertise develops, practice does not clearly differentiate between seeing and thinking or between slides and the anatomy that they indicate.

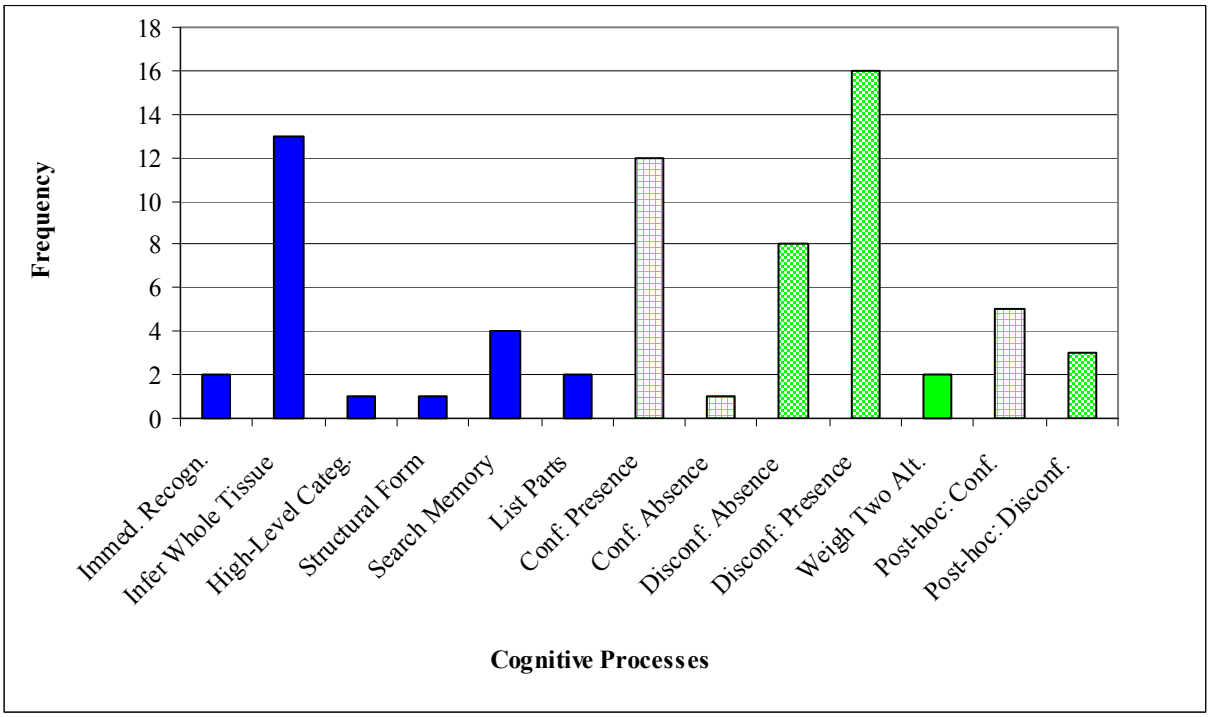

Figure 4. Frequencies of the Elementary Cognitive Processes

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