DOCUMENT RESUME

ED 342 629 SE 052 257

AUTHOR Chi, Michelene T. H.; And Others
TITLE Learning in a Non-Physical Science Domain: The Human Circulatory System.
INSTITUTION Pittsburgh Univ., Pa. Learning Research and Development Center.
SPONS AGENCY Andrew W. Mellon Foundation, New York, N.Y.; Office of Educational Research and Improvement (ED), Washington, DC.
PUB DATE Jul 91
NOTE 39p.
PUB TYPE Reports - Research/Technical (143)

EDRS PRICE MF01/PC02 Plus Postage.
DESCRIPTORS *Biology; Cognitive Ability; *Cognitive Development; *Concept Formation; Grade 8; Human Body; Junior High Schools; *Misconceptions; *Physical Sciences; Science Education

ABSTRACT

This research explores the moment-by-moment understanding students exhibit in the learning of a non-physical science domain--the human circulatory system. The goal was to understand how students learn by capturing the nature of their initial mental models (naive conceptions), and by seeing how new information gets assimilated into their mental models and how their mental models get revised in order to achieve the correct conception. This study reveals that certain misconceptions about the human circulatory system are robust and persistent, but that middle school students are capable of understanding some important aspects of the circulatory system and are then able to modify their existing misconceptions with better and more coherent views. Three major results were found. First, there is a fundamental difference between the physical and the non-physical sciences in terms of how they are learned. Second, aside from historically held misconceptions, which were identified a priori and formulated into questions, the analyses revealed each student's unique set of misconceptions. Third, all 10 students learned the material and although there was a significant difference in the range of the gain scores across the 10 students, such differences were not found to be a function of ability. (30 references) (KR)

Learning in a Non-Physical Science Domain: The Human Circulatory System

by

Michelene T. H. Chi, Mei-Hung Chiu

and

Nicholas deLeeuw

Learning in a
Non-Physical Science Domain:
The Hur an Circulatory System

by

Michelene T. H. Chi, Mei-Hung Chiu
and
Nicholas deLeeuw

This paper was supported in part by an OERI Institutional Grant for the Center for the Study of Learning as well as by a grant from the Mellon Foundation.. The opinions expressed do not necessarily reflect the position of the sponsoring agencies, and no official endorsement should be inferred. We appreciate the help of Joanne Striley for her analysis of secondary texts.

Learning in a non-physical science domain: The human circulatory system

The goal of this project is to understand how students learn science concepts and, in the course of this work, investigate the nature of individual differences in learning. Elementary and high school students learn about many science topics, including those in the life sciences, earth science, space, physical energy, and so on. All require the acquisition of information, as well as the ability to demonstrate an understanding of that information. To do this well, students must be able to acquire new knowledge, link it with existing knowledge, and form a coherent and accessible knowledge structure. Hence, there are many critical issues to explore in understanding how students learn a new science domain, namely: What is the nature of the knowledge structure they build as they learn, what causes them to misunderstand key concepts, how does such misunderstanding relate to their initial knowledge structure, and what kind of instructional help can facilitate their understanding and help them to restructure their initial knowledge when necessary. We begin by first discussing several issues related to the notions of learning.

Learning New Information in the Context of Existing Information

Unless one is learning nonsense material, it is difficult to imagine learning totally new material in isolation. In fact, contemporary research in cognitive science defines "understanding" as the ability to interpret new information in the context of existing knowledge (Brewer & Nakamura, 1984; Greeno, 1977). Bransford (1979), in some of his early work, has demonstrated quite convincingly the necessity of context for understanding a passage. For example, a passage about washing clothes will not be understood unless the reader knows what it is about, so that any given sentence within the passage (such as "The procedure is actually quite simple. First you arrange items into different groups..." Bransford & Johnson, 1973) can be interpreted. In these earlier comprehension types of research, context refers to the general world knowledge that all readers have and share, and to which new information can be embedded and attached. In a learning situation, however, context can be taken to refer to the student's initial knowledge. Unlike the case of comprehension studies, however, we cannot take it for granted that all students come into a learning situation with the same background knowledge. Thus it is mandatory that we assess and know with what knowledge students come into the learning situation.

Bransford also has reviewed the psychological literature showing that learning through the use of strategies such as mnemonics, is equivalent to memorizing some isolated facts by brute force and does not lead to understanding. Bransford, Stein, Vye, Franks, Aubler, Mezynshi, and Perfetto (1982) used the following example to illustrate how using general higher order strategies may limit students' ability to truly understand. Suppose students read a passage about vein and arteries. The passage might contain information about both arteries and veins: that arteries are thick, elastic, and carry oxygen-rich blood from the heart, while veins are thinner, less elastic, and carry blood rich in carbon dioxide back to the heart. To master such a set of facts, the naive student must remember that it is the vein and not the arteries that are thin, that the arteries are the thick, elastic vessels and that the veins carry the carbon dioxide. Weinstein (1978) has taught students to master these facts through the use of mnemonic techniques. Several mnemonics could work here; one could imagine a rubber band holding a tube (the artery) to remember that arteries are elastic, or devise a verbal cue such as "Artery wore pants that had an elastic waistband" (Bransford, Arbitman-Smith, Stein, & Vye, 1985). Although mnemonics are useful in helping students memorize these facts, it is not clear that mnemonics can help students develop an understanding of such facts. Understanding, as defined by Bransford et al. (1985), implies that students can use their knowledge in new situations to make predictions and explain interrelations. Students who mastered information about arteries and veins using mnemonics could not answer questions such as how hardening of the arteries might affect their elasticity, or how the thickness or thinness of arteries relates to the oxygen they are carrying. Good learners must do something more than just memorize a set of facts via the application of mnemonics, since successful learners can explain the significance, interrelations, and causal connectedness of a set of facts (Bransford, Stein, Shelton, & Owings, 1981). Hence, it seems likely that domain-independent general strategies of learning and memorizing are not productive in fostering understanding of new materials. Understanding requires relating the new information to existing knowledge.

The Role of Existing Knowledge or Misconceptions

The realization that learning new information is accomplished in the context of existing knowledge is important for science learning in particular because educators are becoming increasingly aware of the faulty knowledge or erroneous conceptions students have when they enter the science curriculum. It is quite evident by now that by the time students encounter a science domain in the classroom, whether it be mechanics, biology, or astronomy, they have already acquired a vast array of incorrect alternative conceptions. For example, some children (ages 8-11) think that "light from a candle goes further at night,' and "friction only occurs between moving surfaces" (Stead & Osborne, 1980). Moreover, many of these misconceptions persist even after instruction. For example, if college students are asked to draw the trajectory of a ball going off a frictionless cliff at 50 miles per hour, about a quarter of them draw trajectories showing the ball going in a straight, horizontal line off the cliff and then beginning to fall, or curve downward awhile and then dropping straight down in a vertical path. Students making these drawings explain that the force causing the horizontal motion eventually dissipates and is "taken over" by gravity, an explanation incompatible with Newtonian inertial theory. Misconceptions of this kind persist even with excellent formal training, such as that obtained by Johns Hopkins undergraduates (McClosky, 1983). The critical issue, therefore, becomes how one can remove or modify existing misconceptions, and replace them with the correct view.

Research in both cognitive science and science education had flourished recently in documenting these misconceptions, focusing predominantly on the following five issues:

1. what the misconceptions are;
2. to what extent they are resistant to change from instruction;
3. whether there is any developmental progress or improvements in misconceptions across ages;
4. showing that these misconceptions do or do not represent a coherent and stable theory, and;
5. showing that certain confrontation techniques fail to remove misconceptions.

The general finding is that misconceptions are persistent and resistant to change. They cannot be easily removed by either presenting a new piece of correct information or by presenting information conflicting with the existing view (i.e confrontation). When a new piece of correct information is presented that conflicts with the child's view, it is either assimilated into the existing view or ignored. Vosniadou and Brewer's data (1987) present a classic case. Young children have the misconceived notion that the earth is flat. If one tells children (as one would in direct instruction) that the earth is round, their assimilated view is that the earth is round and flat like a pancake. They retain their initial notion that the earth is flat. The point is that misconceptions are difficult to eliminate.

Conceptual Change in Physical Science

Like psychologists and cognitive scientists, science educators have also long known that learning is the interaction between what students already know and what students are taught (Ausubel, 1968). However, after discovering that children's existing ideas are often false and inaccurate and that they persist and distort new learning, science educators have become alarmed and fear that current science teaching is inadequate. For example, Taske (1981) has observed in a naturalistic science classroom that:

1. Students do not link each lesson with previous learning experience, and tend to consider each lesson as an isolated unit of knowledge;
2. Students attribute purposes to each lesson different from the teacher's intended purposes;
3. Students overlook the critical principles that are to be learned from a lesson;
4. Students' existing knowledge is not what the teacher had presumed;
5. Students' understanding after instruction is not what the teacher assumed it would be.

Basically, students misinterpreted what they were taught in order to avoid conflict between the new information and their existing ideas (Osborne, 1982). Thus, the three basic findings in science education are:

1. If children's ideas about science are changed at all by science education, they are not changed in the direction intended;
2. Misconceptions persist even into adulthood;
3. Misconceptions reflect a coherent set of ideas; they are produced by a coherent and integrated, though incorrect, set of conceptual structures (Champagne, Klopfer, & Anderson, 1980).

Science educators have declared that no less than a change in the approach to science education is required (c.f. Karplus and Stage 1981). In particular, curriculum design needs to emphasize children's existing views of the world, and the ways in which educators can "attempt to modify or build on, but certainly not ignore, children's ideas" (p. 492, Osborne & Wittrock, 1983). Furthermore, we agree with Osborne and Wittrock that:

> If such an approach is to develop, and if it is to be synthesized with, and supported by, appropriate research, then it is important that the work has a sound conceptual base (p. 492).

They therefore proposed that cognitive science and cognitive psychology research be consulted in formulating a theory on science learning.

To illustrate, one of the most popular concepts to study in the domain of physical sciences is the notion of "force." The most commonly misconceived notion of "force" attributes it to be a causal property of a body (Nersessian, 1987). Thus, an object which is in motion is said to have a force. Law and Ki (1987) have presented some preliminary evidence showing that students with such a misconception about the concept of force possesses several related rules from which they generate predictions about the motion of objects. A student who views "force" as a property of a body will have several rules about motion:

IF an object's force is supplied by the object,
THEN the object's motion is caused by itself;

and

IF an object is not under the influence of other external force,
THEN the object's motion is caused by gravity.

Such a set of rules for explaining the motion of an object embodies the misconceived causal notion of force. To illustrate how difficult it is to change one's initial conception of force, Law and Ki showed that when students are confronted with a contradiction--for example, of an object's motion which their set of rules cannot explain--they are willing to change only one or a few of their rules, usually by changing parts of a rule, or replacing one of the rules. However, this kind of local patching for the purpose of handling a particular contradiction will not change the students' fundamental misconception that force is a property imparted to a body, to the correct conception that force is a quantitative relationship resulting from the interaction of two or more bodies. Although it has limitations, this study is one of the clearest and most direct analyses of failure of conceptual change, using a direct confrontation approach.

Conceptual Change in Biology

In this section, we briefly present our argument that learning in a biological domain may not require the same kind of conceptual change that is necessary for a physical science domain, at least in the subtopic that we are investigating--the human circulatory system. This conclusion follows from a comparison of the structure of knowledge in a biological science domain with the structure of knowledge in a physical science domain. We have derived four dimensions of differences between a physical science and a biological science domain, thereby leading us to conclude that one requires a radical kind of conceptual change in order to learn the content, and the other one does not. (We will explicate the meaning of radical conceptual change later.)

1. The nature of explanations. According to the literature in the philosophy of science, in a physical science domain such as mechanics, explanations of phenomena basically require nomological deductions from principles, which are regularities that are expressed in mathematical equations. In a non-physical science domain, however, explanations often require an explication of the mutual interactions of the components of the system to be explained (Haugeland, 1978). An explanation of the circulatory system, for example, requires explication of the functional, structural and behavioral inter-relations between the heart, the blood and the vessels. Therefore, knowing how each component works is not, in itself, sufficient for understanding the function of the circulatory system, which *is* the organized interaction of the components.

2. The nature of the misconceptions. It seems necessary to differentiate between children's misconceptions in a physical science versus a nonphysical science domain. In a non-physical science domain (such as the topic of the human circulatory system) misconceptions seem to arise from three sources. First, misconceptions may be due to a lack of knowledge. For instance, elementary school children tend to think of blood predominantly as a red liquid (Arnaudin & Minzes, 1985), which is correct in the sense that it is consistent with their sensory experiences. They imply do not know that blood has other constituents (such as red

cells). Secondly, misconceptions may occur because the entities are not readily observable and /or accessible. For example, not being able to see that valves exist could hinder children's understanding of how blood can flow in only one direction. (In fact, discovering the existence of valves was a major breakthrough in the historical development of circulatory theories.) Third, misconceptions could arise because of the complexity of covert processes, such as circulation and photosynthesis. Both of these processes are complex because they involve relations among several entities (circulation involves the heart and the lungs) in an intricately causally connected way.

Concepts in the physical sciences (such as current, force, light, heat) are difficult to understand not because they are covert or non-observable, so that one's sensory experiences of them deviate from their actual qualities. Rather, we suggest that these concepts are difficult to learn because people treat them as types of material substances or attributes of material objects, when in actuality, they are types of "constraint-based" events (Chi, in press). For instance, force is conceived of as a kind of impetus that can be imparted by an object, as when a ball is thrown. The scientific notion of force is that it is an event, which exists under the constraints of other entities. A force does not exist, for example, unless an object is moved into a force field. Thus, a metal ball does not experience a force unless a child moves it within the range of a magnet. The implication of this difference between naive notions of these physical concepts and their accurate scientific notions is that they belong to different ontological categories. Ontological categories are fundamental categories of existence in the world, such as differences between material substances and events. Therefore, conceptual change is radical if learning requires a change in the identity of a concept from one ontological class to another. This means that in order to understand the scientific meaning of a physical concept, students' existing conception of them must be replaced rather than modified, since understanding their scientific meaning requires a shift in its ontological status.

3. <u>The pattern of misconceptions</u>. Difference in the nature of naive conceptions about the two kinds of science domains can be substantiated by a pattern of empirical evidence. In a physical science domain, misconception most frequently are similar across students, robust and persistent, and very difficult to overcome by either instruction or confrontation of any kind. Furthermore, there appears to be a general underlying similarity across the misconceptions of many of the physics concepts, such as force, light, heat, and current, in that the students treat all of these entities as if they are a kind of substance (Reiner, Chi & Resnick, 1988). Finally,

there is a similarity in the misconceptions held by medieval scientists and contemporary students.

This pattern of results, namely in the consistency and robustness of misconceptions in the physical sciences (a) across studies, (b) across concepts, (c) across ages, (d) across educational levels, and (e) across historical periods, is not obtained for a domain in the biological sciences, such as the circulatory system. Although less work has been done in identifying biological misconceptions, it is clear that there is much less consistency across students in what their misconceptions are; nor does there appear to be any systematic underlying structure. (See, for example, Arnaudin & Mintzes, 1985.) The most reliable pattern is that many students appeal to a lack of knowledge rather than holding on to persistent misconceptions.

4. The nature of learning the domain content. As we have alluded to earlier and discussed extensively in Chi, (in press), since naive physical science concepts are represented as types of material substances, and their correct scientific meanings categorize them as kinds of events, then learning their correct meaning would require a shift across ontological categories. This kind of conceptual change is radical and difficult to achieve (Chi, in press). Learning some biological concepts, on the other hand, does not require such a radical conceptual shift. This is because the naive and scientific conceptions of certain biological concepts are not ontologically different, so that straight-forward acquisition processes such as addition, deletion, and refinement of existing beliefs, can account for their learning.

In sum, four dimensions of differences can be captured between a domain in the physical sciences and a domain in non-physical sciences. Their differences have important ramifications for how they are learned. We do not intend to suggest that no ontological shifts are needed for all conceptual changes in non-physical science domains, but rather, that this distinction of whether or not conceptual change requires an ontological shift should be heeded in understanding learning and in prescribing instruction.

Choice and analysis of a biological domain: the circulatory system

Our study focuses on the circulatory system as an example of a biological domain. This domain was chosen for various reasons. Pedagogically, we chose biology because contemporary students have been shown to have inadequate understanding of biology in general. The National

Academy of Science Committee has recently stated that the current biology curricula used in most schools are "a crammed and outdated failure" (Rothman, 1988). According to the committee, American students ranked last among 16 nations in their achievement levels in biology. The need for better understanding of biology is seen as mandatory in order that students can better relate to issues which they will encounter for the rest of their lives, such as AIDS, global warming, and genetic engineering. We choose the circulatory system specifically mainly because it has been ranked in the top five most important topics to be learned in biology (Stewart, 1982). (The other four topics are inappropriate because they were not introduced in the lower grades at all, so that they had to be eliminated since we foresee doing a longitudinal study.) Also, contemporary approaches to preventive medicine also requires that students have some basic understanding of the circulatory system.

There are a number of additional pedagogical reasons why the circulatory system is a good choice of domain for stuay. First, circulation is a complicated system to understand. Several key ideas present stumbling blocks for both the students and earlier generations of scientists. Second, because students do not understand certain key ideas, a significant number of misconceptions exist. For example, student have difficulty understanding that circulation consists of a double pulmonary and systemic pattern of blood flow (Arnaudin & Mintzes, 1985).

Theoretically, this choice of domain allows us to examine complex causal structures and their constraints on causal reasoning more closely. Causal reasoning is a fundamental process by which students explain physical and biological events. The success of causal explanations depends largely on the domain representation, particularly the degree to which it is integrated. The circulatory system will allow us to capture the kind of representation of causal knowledge that most effectively leads to causal explanations. To illustrate, understanding the circulatory system requires "systematic" explanation (Haugeland, 1978), in that one must understand the "organized cooperative interactions" that occur within the system. Such cooperative interaction can be explained by the systematic interaction of the distinct components at all levels of the system. One way to specify this organized cooperative interaction is to decompose the circulatory system into its components and identify the structure, function, and mechanism of each component. We operationally defined each physical entity such as heart, atrium, blood, etc., as a component. There are three aspects to each component: the structure, function or purpose, and the behavior. Take the heart for an example. The structural properties of the heart are that it is composed of a large muscle and four chambers, and so forth. The function of the heart can also be specified directly--it pumps blood. The behavior of the heart is that it expands and contracts. However, the most important relation that is often left unspecified in textbooks is the causal one. That is, how does the heart, being made of muscle, relate to its function of pumping blood? How does the structure relate to the behavior? And how does the behavior relate to the function? These relations between the structure, function, and behavior of each individual component will be referred as *local relations*. (The behavior of a number of interacting components will be referred to as the *mechanism*. For example, the mechanism of diffusion refers to the behavior of a number of interacting components, such as the cells, the membrane, the density of one kind of cells over another kind in the blood, and so forth.) In addition, in order to understand the whole system, some causal relations between the structural, behavioral or functional features of different components have to be specified also. These relations which cut across components will be referred to a *global* relations. For instance, one feature of the heart is that it has two sides. Although this structural feature of the heart does serve the purpose of separating oxygenated from deoxygenated blood ***within*** the heart (a local function), it is also related in an even more important way to optimizing the functioning of the circulatory ***system*** as a whole (i.e., it allows for separate pulmonary and systemic circulation). Thus, in order to have a coherent understanding of the circulatory system, an intricate system of causal relations must be specified among all the components, relating their structural features, their component functions, as well as the functioning of the system.

Because it is a causally related system, it affords the opportunity to find integrated and consistent misconceptions more readily. That is, if there is any systematicity in the structure of misconceptions about the circulatory system, they will be more directly displayed since the circulatory system is dynamic, involving various parts working together in an integrated way to achieve the goal of delivering nutrients to the body and ridding the body of wastes. That is, causal and temporal dependencies between series of system events are present, as well as causal relations between the structure and function of various components. Thus a misconception about the structure or function of a system component, or about a particular sequence of events, can have repercussions for the conceptions of many other aspects of the system. Misconceived notions about one component will have definite ramifications for the functioning and behavior of another component. Students' integrated (mis)understanding should be capturable if it exists.

Pragmatically, the circulatory system is a good choice as a research domain because its entities seem more concrete and easily separable into their structure, function, and relations, as compared to mechanical entities. For example, the entity "heart" is a concrete object with a physical structure, definable functions, and relations with other entities in the circulatory system (such as the lungs). We claim that the virtue of using biological concepts such as circulation is that such concepts allow us to isolate where misunderstanding occurs; that is whether it has to do with a lack of knowledge about the entities and their properties, or whether it occurs at the level of the relationship between the entities.

Finally, Harvey's discvoery of how blood circulates in a double loop was hailed as a major revolutionary breakthrough in the history of sciences, on par with the Scientific Revolution of the Newtonian era. Thus, studying the learning of the circulatory system would allow us to compare and contrast the nature of conceptual change in these two domains--the circulatory system and basic physics.

Analyses of Text

We began by examining eight or more texts that contain units on circulation and came up with a composite set of materials generally covered in the unit on circulation. We will, therefore, also restrict the material of our study to this list of topics, which is shown in Table 1, because the nature of our study will not permit in-depth coverage of very broad knowledge domains, although there will be materials on the relationship of the circulatory system to the respiratory and immune systems (see sections 6A and 6B in Table 1).

Table 1

The Circulatory System

1) Overview and Principles
    A) Transport system: bring nutrition and excrete waste, idea of exchange
    B) Double rather than single circulation (Internal Transport)
    C) Closed vs. open

II) Source of the Transport: Heart
    A) Structure
    B) Function

III) Medium of Transport: Blood
    A) Content of the substance
        1) red cells
        2) white cells
        3) platelets
        4) plasma
    B) Path of blood circulation

IV) Mechanics of Transport: Vessels
    A) Arteries
    B) Veins
    C) Capillaries

V) Mechanisms of Transport or Flow
    A) the role of muscle acting as a pump
    B) The effect of pressure and gravity in effecting flow
    C) The mechanism of osmosis in transferring nutrients and waste

D) The role of hemoglobin in transporting oxygen and carbon dioxide

VI) Relation to Other Systems:

A) Respiratory

B) Immune

Table 2. Types of Information Shown in a Text.

1. Some general remarks about the global function of the circulatory system, such as its role in delivering nutrients and removing wastes;
2. Factual knowledge describing the physical properties and structure of each component of the circulatory system, such as the muscles of the heart;
3. The behavior of a component, such as how valves open and close, or the direction of blood flow;
4. The local function or purpose of each component, such as the purpose of valves;
5. Descriptions of mechanism such as diffusion or oxygenation, which include the components involved and the processes that occur;
6. A variety of relationships among the five kinds of information above, such as relating the structure to the local function, relating the structure to the mechanism, and so on;
7. Relating a local structure, functional, or behavior to the global (or system-wide) function of the circulatory system.

Several kinds of information can be contained in a text as shown in Table 2. It appears that, in general, most of the texts are more or less adequate in explaining the first three factors. There are some deficiencies in the other factors in terms of the incompleteness of the account. We can illustrate the shortcomings even among the best texts. We chose four highly rated texts from recent reviews of secondary biology textbooks in the AAAS publication, ***Science Books & Films*** (Johnston, 1985, 1988), and subjected them to further analysis. The chapters in these texts dealing with the circulatory system all display the same basic structure. A statement of the general functions that circulation serves (Factor 1) is followed by an exposition of the parts of the human circulatory system: the blood, blood vessels, and heart (Factors 1 & 2). The text differ chiefly in the extent to which they relate anatomical structure or function to physiological functioning of the entire system (Factor 7).

Two of the slightly less highly rated texts present short overviews of the functions of circulation and then focus on the structure and properties of the components of the system (Factors l, 2), chiefly by naming and describing parts (Factor 2). An example of this approach is given in the following section from Kormondy and Essenfeld (1988) describing the heart:

> At rest, the average human heart beats 72 time and pumps 5 L of blood every minute. During strenuous exercise, the heart may beat 170 times and pump 20 L of blood per minute. By the time a person reaches age 75, the heart has beat nearly 2.8 billion times and has pumped about 390 million liters of blood. This is remarkable considering that the heart is about the size of a clenched fist and has a mass of only about 300 g.
>
> The human heart consists of four chambers. Two thin-walled chambers at the top of the heart, the ***atria*** (AY-tree-uh), received blood from the veins. Two thick-walled chambers at the bottom of the heart, the ***ventricles***, pump blood into the arteries. The chambers of the heart beat in an orderly sequence. First the atria contract, then the ventricles contract. Each chamber relaxes after it contracts. (p. 238)

Although this passage contains facts about the heart, it does not dwell on how the local mechanisms (pumping of the heart) participate in the global purpose of achieving the system's goal of circulation (Factor 7). These texts are traditionally organized, moving in a hierarchical way from micro tc macro structures: cells to tissues to organs to systems. The emphasis on local structure and functions can also be seen in three typical end-of-chapter exercises:

1. State the part of the body described by each of the following functions: a. carries blood to the heart, b. produces red blood cells, c. prevents backflow of blood in the heart.
2. Explain the difference in function between the left ventricle and the right ventricle

of the heart. How is each one adapted for its particular function?

3. A heart removed from the body continues to beat. Which structure makes this possible?

The two most highly rated texts do spend more time developing functioning of circulation and relating local structure and function to the global purpose, as seen in the following example for Andrews, Purcell, Balconi, Davies, & Moore (1980):

> Birds and mammals have ***four-chambered hearts in which both atria and ventricles are completely separated*** in the adult. Oxygenated blood, found only in the left atrium and ventricle, is completely separated from deoxygenated blood in the right atrium and ventricle.
>
> Birds and mammals are warm-blooded or homeothermic animals. Their body temperatures and metabolic rates remain relatively high and constant despite changes in environmental temperatures. As a result, a highly efficient transport system is required to maintain both a high temperature and a high metabolic rate in the vertebrates. (p. 530)

The organization of these texts is governed by certain relations (e.g., the passage above relates heart structure to energy requirements), and their review questions require the student to apply them. Even in these best texts, however, the ways in which the local mechanisms serve the global functioning of the entire system are not explicated. The first paragraph above, for example, does not make it clear to the reader why oxygenated blood needs to be separated from the deoxygenated blood, or why this is beneficial. In the second paragraph, it is not explained why an efficient transport system is required to maintain both a high temperature and a high metabolic rate.

When the design of the texts is inadequate, there are two alternative routes one can take to improve instruction. The most obvious one is to modify the text. This seems to be an effortful and futile exercise since there are thousands of texts out there that are inadequate, and infinite number of them to come in the future. This approach would require either revising all existing texts or instruct text-writers to write them more clearly. Moreover, texts can be inadequate not only in their treatment of the content, but in their rhetorical styles as well, such as vague topic sentences, ill-defined organization, and so on. The alternative route to understanding how students comprehend such texts is to see what kind of mental models they construct as they read. Capturing how students cope with inadequate texts as a function of their existing mental models (or initial conceptions) could inform us of ways to teach students to handle print information in general. The goal of this research is to see how students understand scientific texts as a function of the *ongoing* mental models that they construct and revise.

Method

Procedures

The design of our study is very straight-forward. There are three phases to the study that involved eighth graders who have not had a formal unit on blood circulation in that semester:

1. An initial interview session (a pre-test) in which each student answers a set of preconstructed questions; this interview is taped.
2. Each student then reads the selected standard text. While reading, the student is encouraged to talk out-loud at the end of every sentence, explaining what they are thinking. Their "explanations" or elaborations should provide us with rich source of data revealing the kind of inferences they draw to integrate what they are reading with their existing knowledge; that is, on how they are assimilating the material they are reading. They may also take notes and draw diagrams while reading.
3. After they have read the material, students answer two sets of questions, one set is identical to the one given in the pretest above.

Selection and Coding of Text

The unit that we have chosen is taken from Modern Biology (Towle,1989), a popular and highly-rated biology text commonly used in junior and senior high school. We kept the unit intact, covering most of the topics described in Table 1, except that the three (not very informative) figures and a few sentences were deleted to keep the unit short (containing a total of 101 sentences). The sentences included in the text relate to the major components of our interest. We deleted sentences which referred to figures in the original textbook, as well as excursions into related topics that were not mandatory for understanding the primary topic, such as lymphatic system.

Consistent with other good texts that we have reviewed in the prior section, this one also contains information characterized primarily by Factors 1-3 of Table 2. With respect to Factor 4, this passage explicitly discussed 11 out of the 22 components' functions. The rest of the components' local function, such as the purpose of skeletal muscle, were not specified. Even when the local function of a component is explicitly specified, their purpose is usually not related to the global function of the circulatory system (i.e., this passage is also deficient in Factor 7). For instance, the sentences in Table 3 indicate the purpose of the pulmonary system and valves in the veins. However, they do not state why the pulmonary vein does not have a valve in it. Therefore, the students must make coherent inferences in order to construct a complete mental model.

Table 3. Sentences Indicating Purposes of the Pulmonary System and Valves in the Veins.

Line #	Sentence
73)	Valves prevent the blood from moving backward or downward.
80)	Pulmonary circulation is the movement of blood from the heart to the lungs and then back to the heart.
86)	Oxygenated blood then flows into venules, which merge into the pulmonary veins that lead to the left atrium of the heart.
87)	The pulmonary veins are the only veins that carry oxygenated blood.

Coding of text

Each sentence of the text was coded as to what type of information it contained. The categories were purpose, structure, behavior, and factlet. Each sentence contained one or more type of information, pertaining to one or more components of the circulatory system, and/or relationships between components. Mechanisms such as diffusion generally require several sentences to describe. Thus, mechanisms are really the interactions of structure, function, and behavior. The symbols for coding and examples are listed in Table 4. The same technique was systematically applied to coding of the questions that we designed.

Table 4. Coding Scheme and Examples.

P = Purpose	S, B = S and B
S = Structure	S - B = S related to B
B = Behavior	S --> B = S implies B
F = Facetlet	S/B = S or B

Examples:

B (Heart)
Line 8: The heart rate can change, however, depending on a person's activity level.

S, B (valve) -- B (Blood)
Line 28: Each of the valves consists of flaps of tissue that open as blood is pumped out of the ventricle.

The purpose of such coding is to permit a direct assessment of the extent to which the kind of knowledge needed to answer a question is or is not provided by the information in the text.

Selection of Students The students were 10 eighth graders (4 males and 6 females) recruited from a local public school. None of them have taken a biology course. We intentionally chose students with a range of abilities in terms of CAT scores, so that we could examine learner differences (for the purpose of contrastive analysis.) The CAT scores ranged from 65.33 to 99.00 points. The mean CAT score of the five highest students is 97.07 (s.d.=1.57) points (they will henceforth be referred to as Hi-Ability students) and the mean CAT score for the five Low-ability students is 78.67 (s.d.=10.18) points. Thus, the difference between the two groups span about two standard deviations. Students were paid for their participation.

Design of Questions Six sets of questions have been constructed to tap students' knowledge of this topic prior to studying the text, as well as their understanding after reading the text. Three sets of questions (Categories 1, 2, 3) were designed explicitly to test what was learned from the text. Three other sets of questions were designed to test their prior knowledge or misconceptions as well as their use of this knowledge to answer health-related problems. Category 1 questions are to be derived from information explicitly stated in the text. They represent a single relation between 2 arguments. Usually the information is presented in a single sentence, but occasionally an implied agent from the previous sentence is needed. Thus, these questions could be about the structure, function, or simple statements about the mechanism, as directly or explicitly presented in the text.

Category 2 questions have answers explicitly presented in the text as well, but they require the student to integrate information from two or more lines of text, or integrating across disparate paragraphs which are presented at temporally different points in time, rather than consecutively.

Category 3 questions require inferences, which can be generated from the text materials if the student understood them. These inferences vary from local ones to global ones which require a complete understanding of the entire circulatory system. For instance, if a student understood that the circulatory system is closed, then she would be able to generate inferences directly from that understanding, such as that there would not be an increase or decrease in the total volume of blood in the system.

Category 4 questions concern historical misconceptions, that is misconceptions held by medieval scientists. These are constructed to test the notion that contemporary conceptions and historical ones may not be similar, as is the one in physics. The questions address whether students entertain ideas similar to the misconceptions of medieval scientists of Pre-Harvey era.

Category 5 consists of health questions. Students should be able to answer these questions on the basis of what they have learned from the text. That is, they should be able to apply the knowledge that they have learned from the text, in conjunction with some common-sense background knowledge, to answer these questions.

Category 6 questions concern interpretations of historical evidence. These questions present historical evidence which led medieval scientists to discoveries about the circulatory system. We want to determine whether students interpret these evidence in the same way as medieval scientists. This addresses the notion that such interpretation of evidence is not difficult if contemporary students do not have the same initial mental model (or misconceptions) as medieval scientists, as may be the case in the domain of the human circulatory system.

Besides these questions, students were asked to define 23 terms taken from the circulatory system, and asked to explain "everything you know" about those circulatory-related terms (e.g., blood vessels, capillary, diffusion). The questions listed below served as cues to remind students of anything that they might already know about them.

1) What is it? What kind of thing is it? What does it refer to?
2) Where is it found in the body?
3) What is its structure, texture, or composition?
4) What does it do?
5) What is its purpose?

After taking this task, students were also asked to depict their conception of how the blood travels through the body (including the heart, lungs, brain, feet, and hands) given an outline of the human body. They were also required to use arrows to indicate the direction of flow. Protocols were taped while drawing.

In addition to questions and terms, there were 22 probes inserted in the text to examine whether students can explain the function of a component as a function of whether it was explicitly mentioned or not.

Preliminary Findings

Cross-sectional results

Gain Scores.

Most of the students learned from this task. The overall percentage of correct answers on the pre-test was 39.82 (s.d.=9.88) and the overall percentage of correct answers on the post-test was 67.37 (s.d.=11.02; this difference is significant at the .001 level, $F(1,9) = 74.997$). Figure 1 is a breakdown of overall pre-test and post-test scores according to the 6 categories of questions that we have designed (See Table 5 for percentages of correct answers for each category). As one can see, the biggest gain is in Category 1 (38.85%, s.d.=19.71, $F(1, 9) = 38.85$, $p < .001$) which taps information explicitly presented in the text; and the smallest gain is in Health questions (13.89%, s.d.=13.72) which require application of the knowledge they gained from the text as well as some background knowledge.

Figure 1. Percentage of correct answers on pre- and post-tests by categories of questions.

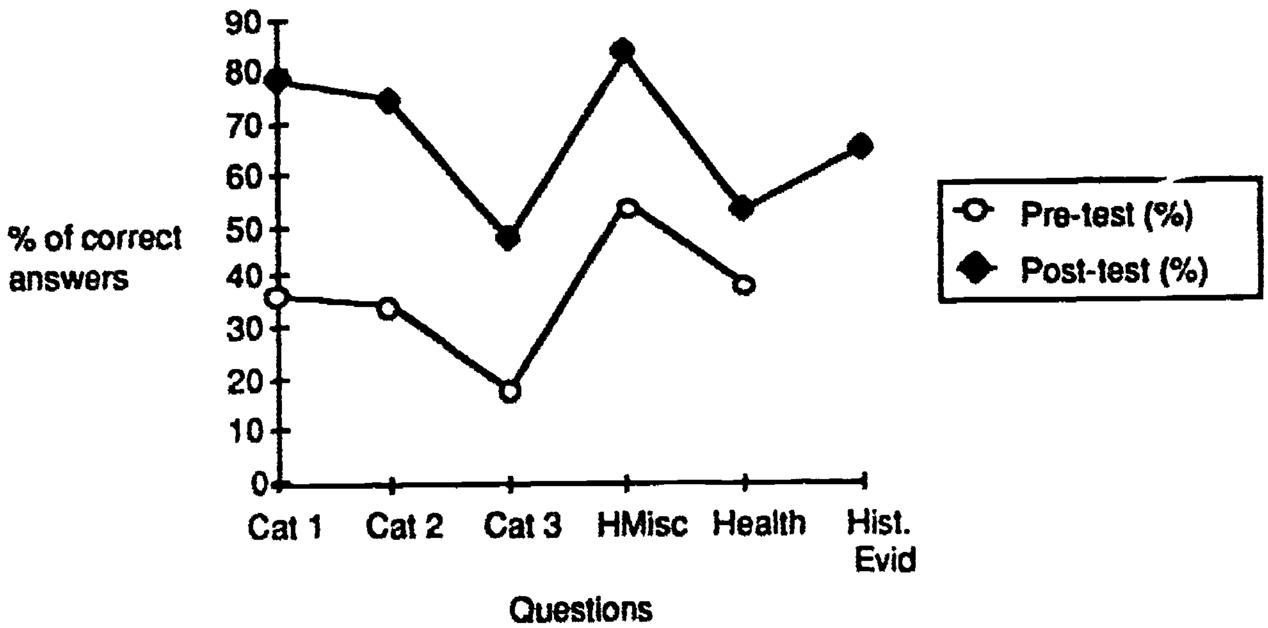


Table 5. Percentages of Correct Answers for Overall and Individual Category on the Pre-test and the Post-test.

	Pre-test (%) M SD	Post-test (%) M SD	Diff (%) M SD	F-test
Overall	39.82 (9.88)	67.37 (11.02)	27.55 (10.06)	74.997**
Misconceptions	54.94 (12.04)	83.16 (11.16)	28.22 (14.76)	36.587**
Cat1	39.03 (12.48)	77.88 (10.34)	38.85 (19.71)	38.85**
Cat2	35.62 (15.63)	73.87 (13.13)	38.25 (21.78)	30.851**
Cat3	17.90 (15.19)	47.18 (19.02)	29.28 (15.21)	37.071**
Health	38.33 (14.75)	52.22 (14.85)	13.89 (13.72)	10.252*
Hist. Evid.	.	64.50 (18.06)		

** at .001 significance level, * at .05 significance level

We also found that there was no difference between Hi and Low ability students on individual category questions and the subset test (See Columns 1 and 2 of Table 6). This lack of difference between Hi and Low ability students seem contradictory to findings in the literature at large. However, one of the intended manipulation of this work was to see how effective an instructional intervention such as prompted elaboration or self-explanation would be for learning. Since all the students learned using this enforced elaborative mode, perhaps this explains why there is no ability differences.

However, there is a significant range of performance differences among the 10 students if we do a medium split on their gain scores (3rd and 4th columns of Table 6). The top 5 students (in terms of overall gain scores) answered significantly more questions correctly than the 5 poorest-performing students; this overall difference can be attributed primarily to questions in category 2 and category 3 which require more integration and inferences for accomplishing the task.

Table 6. Percentages of Correct Answers for each Category on Overall Difference between Pre-test and Post-test by Level of CAT and gain scores.

Items	Low CAT		High CAT		Low Gain		High Gain	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Overall	27.55	(13.03)	27.56	(7.62)	20.39	(5.55)	34.72	(8.28)*
HMisc	34.35	(16.14)	22.10	(11.64)	25.73	(7.9[illegible]	30.72	(20.26)
Cat1	38.95	(26.82)	38.75	(12.45)	31.03	(25.62)	46.67	(8.05)
Cat2	37.58	(28.84)	38.92	(15.30)	21.54	(9.64)	54.96	(16.62)**
Cat3	31.18	(14.83)	27.38	(17.07)	20.06	(10.58)	38.50	(14.00)*
Health	7.5	(8.81)	20.28	(15.61)~	14.72	(7.12)	13.05	(19.26)

** p < .01   * p< .05   ~ p< .10

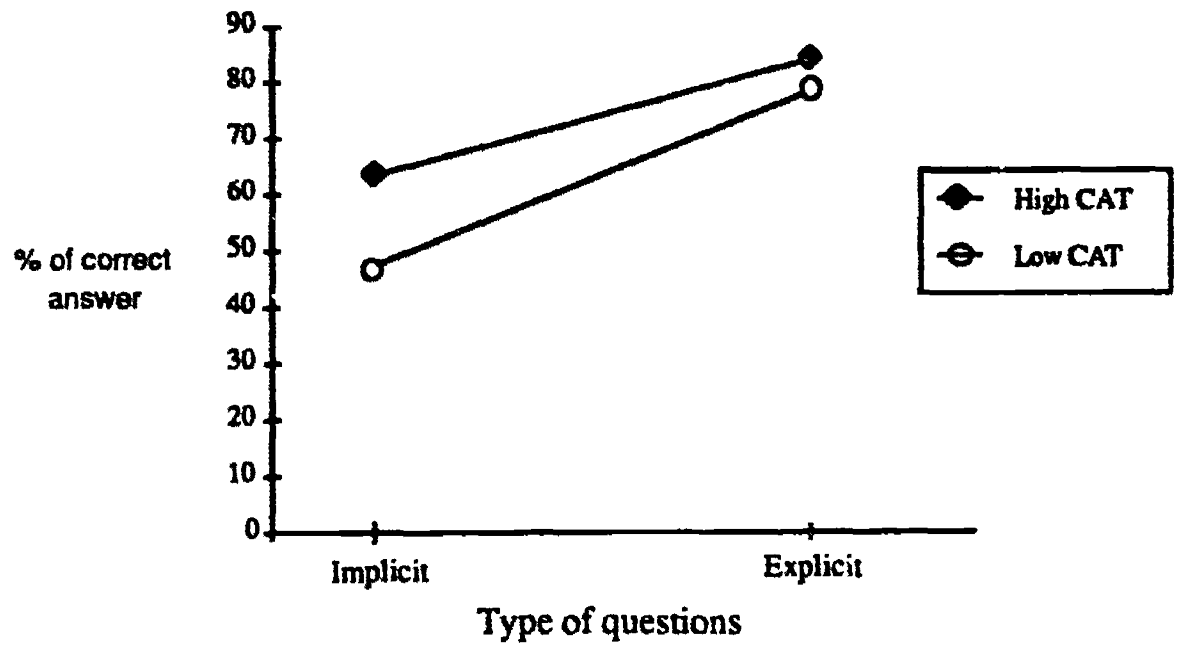
Misconceptions

The misconception set of questions were targeted at assessing whether contemporary students held the same misconceptions as medieval scientists, and whether these could be easily removed from instruction. The students correctly answered 54.94% (s.d.=12.04) of the Misconception questions on the Pre-test, and 83.16% (s.d.=11.16) on the Post-test ($p < .001$, $F(1,9) = 36.587$, see Table 5), and there were no significant differences between ability groups (High=22.10, s.d.=11.64; Low=34.35, s.d.=16.14, See Table 6). This confirms our hypothesis in the following two ways: First, that misconceptions held historically are not widely shared by contemporary students--contemporary students share only about half of the misconceptions that medieval scientists held. Second, the improvements in the post-tests score suggests that the majority of the misconceptions can be easily removed by instruction. In contrast, in the case of physics, contemporary students hold misconceptions very similar to those held by the medieval scientists, and furthermore, they are very difficult to remove (see evidence cited in Chi, in press). These two pieces of data support our conjecture that there is a fundamental difference between the physical and the biological sciences in terms of the kind of conceptual change required for learning them.

Induction of Function

We noted that one of the major shortcomings of the text is an incomplete specification of the functions or purposes of components, since such knowledge is necessary for causal understanding. Accordingly, we probed for such knowledge at pre-specified locations and see the extent to which students can induce the function and use it without being explicitly told. We have classified questions which pertain to the function of a component as EXPLICIT questions if they assessed function information that is explicitly mentioned in the text. On the other hand, IMPLICIT questions require inferences about the function of a component from the text. As expected, we found that overall, students performed better on EXPLICIT (mean=81.83, s.d.=18.03) than IMPLICIT questions on the post-test (mean=55.52, s.d.=20.14, F=17.129). However, there is a significant difference between Hi and Low ability students in their ability to answer IMPLICIT questions (F=7.813 at .05 significance level, See Figure 2) but not for the EXPLICIT questions. This suggests that the High ability students were more able to infer the function from the text. Subsequent analyses that we plan to carry out will explore how the Hi ability students achieve this kind of induction.

Figure 2. Means for Percentage of Correct Answers on Explicit and Implicit Functional Questions by Ability.



Note-taking.

In addition to talking out-loud, students were encouraged to take notes while reading the materials. Students' notes were categorized in three formats: re-producing the sentence, re-organizing the information, or drawing diagrams showing the interrelationships among the components of the circulatory system. As they generate notes or diagrams, they were asked to elaborate their understanding about the presented information. Number of notes and diagrams taken was recorded.

In general, there was no significant differences in numbers of notes or diagrams made between Hi and Low ability students. Furthermore, if we compare the top five students (in terms of overall gain scores) with the five poorest-performing students, we still find no difference in the number of notes they took. However, there is a strong difference in the number of diagrams drawn by the five best students (15.2 diagrams) versus the 5 poorest students (8.8), although the difference did not reach statistical significance. We conjecture that diagrams are more helpful and powerful in helping students "see" the inter-relationships among the components in the circulatory system, so that drawing them might help the students modify their mental models. Notice that the activity of drawing must have facilitated performance since there was no correlation between the number of diagrams drawn and ability scores. This evidence might provide some insight of the efficacy of assisted tools in learning even though the result did not show the difference to be significance. Analysis with more students are needed. Furthermore, the quality of the drawing might need further investigation.

Individual Student Analyses.

Misconceptions.

In the previous section, misconceptions were assessed by the questions we have designed. Students were attributed with having a misconception if they answered a misconception question incorrectly. Furthermore, these misconceptions were based on historical evidence of the kind of misconceptions that medieval scientists held. In this section, we describe analysis in which the entire student's answers and reading explanations were analyzed for individual misconceptions. This allows us to capture misconceptions that different students have that we do not know about in advance.

Our analysis embeds the misconceptions in the context of the student's mental model of the entire circulatory system. We substantiate our analysis of the misconceptions by the comments and answers that the student gave. Only when two or more independent comments and explanations given that are consistent with our interpretation of the student's misconception, did we then attribute the student with a given misconception. For example, in analyzing NA's data, we found that she had basically five independent misconceptions. Many of her misconceptions were partially incorrect only. So for instance, she has the notion that the circulatory system is closed (which means she should also know that the volume of blood does not change, and also that the blood is enclosed), but thinks that it flows in two directions within the same vessel (rather than circulates). The following four quotes plus a drawing in her note, support our interpretation:

p. 2 (Bloodpath) "The blood goes out, but, it goes both ways, in and out"

p. 3 (bloodpath) "It (blood) goes all the way through and around because there is no way ... It doesn't excape [escape] unless you have a cut or sore or something

p. 7 (HMisc-4) "...it [heart] doesn't decrease the [in the total volume of] blood...it just, the heart just pumps it slower [when it's not functioning properly]."

p.17 (2-12) "I think it [blood in vein] does [flow in both directions] because if it

> didn't flow in both directions I don't know where else it would go and since it is continually moving it has to come back."

On the basis of such analysis, Student NA. had five misconceptions. Of these, only one misconception persisted after reading from the text.

In order to understand how misconceptions in the mental model persist or are removed, we need to examine in greater detail how learning takes place. That is, learning can be viewed as the confrontation between one's initial incorrect mental model and the assimilation of the correct information presented in the text. Our theoretical explanation for persistance or removal is the following. If a student's existing mental model can assimilate a new piece of information without conflict, then the original misconception will persist. Misconception can only be removed if a new piece of information directly challenges a student's mental model. Note that most of the confrontation approaches used in the literature do not directly challenge a student's mental model; instead, they challenge the student's predictions and explanations, which can be readily rejected by the student as irrelevant or explained away by adhoc reasons. Direct challenge to the students' mental model, however, is more difficult to be rejected outright. We illustrate these occurances below.

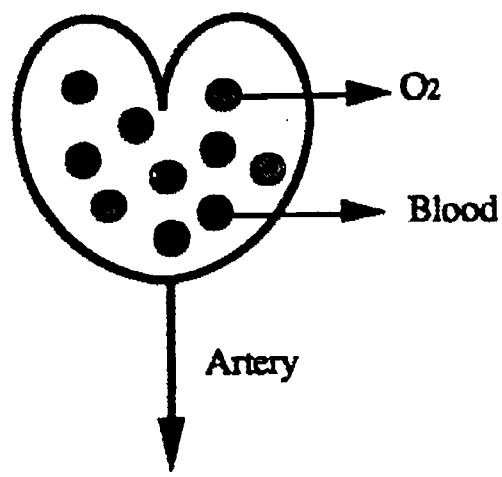
Persistance of misconceptions

AG began our study with a fair amount of correct information about the circulatory system, and also with a variety of Misconceptions. She also developed a small number of new misconceptions during the study. Most of her old and new misconceptions were removed during the course of the study, but not all in the same way. Misconceptions which were directly confronted by the text were removed quickly. This is illustrated by her initial bloodpath through the heart, which will be discussed at some detail. On the other hand, misconceptions which were not directly challenged were removed only slowly, if at all. This latter type of misconception can be illustrated by examining her notions of oxygenation, in the heart.
At the onset of the study, AG believed that oxygenation occurred in the heart, rather than in the lungs. Although this is not correct, it is not directly contradicted by the text. Instead, this misconception is challenged indirectly by the correct information about the heart and lungs. That is, the heart's purpose is to pump blood, and oxygenation occurs in the heart. This correct information led to a series of incremental revisions of AG's mental model, which only gradually

replaced her initial misconception.

The gradual removal of this misconception can be better understood through a brief examination of her initial mental model and the subsequent revisions to it. The following passages, from the pre-test terms, illustrates some of her initial model (See Figure 3):

Figure 3: AG's Initial Mental Model of Oxygenation in the Heart



[Blood] travels back up in the veins to go back to the heart, the heart cleans it again... replenishes it with oxygen... and then it goes again to all the parts of the body.

...The Lungs they're over the heart umm.. there are two of them. They're just like a lot of air sacs basically. You breath in oxygen and the lungs fill up and then you breath out carbon dioxides and the lungs like contract and when you breath in again they expand.

AG demonstrates that she understands the concept of oxygenation (replenishing the blood with oxygen), but misplaces where it occurs. She also demonstrates that she knows that oxygen enters the body through the lungs, but not that it enters the blood there.

This initial model gets elaborated in the course of the pre-test and the readings. In the pre-test she encounters the question, "Does the pulmonary artery carry air?," and is forced to consider the issue of oxygenation in the lungs. Her response illustrates an addition to her model. First she states that air does not travel through arteries, only blood does.

I don't think arteries carry air at all. Umm... arteries carry blood.

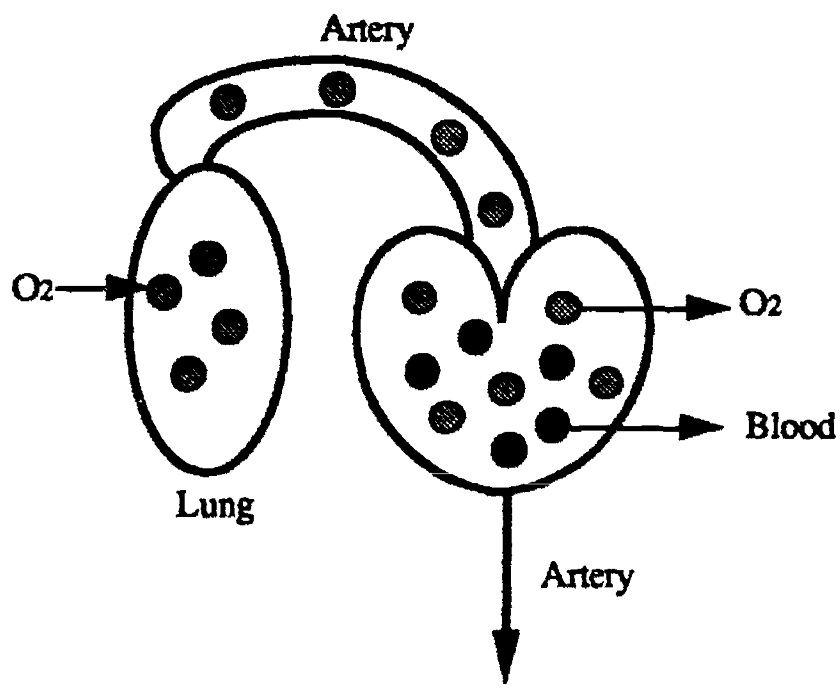
But she allows that an artery carries oxygen:

Because all arteries carry oxygen. Umm... I mean that's what they do.

So it makes sense that the pulmonary artery could carry oxygen from the lungs to the heart:

...you breath in the air it goes through the lungs, the lungs umm... get the oxygen, so they [the oxygen] go to the heart, the heart has the oxygen to give to the arteries, ... to the blood (See Figure 4).

Figure 4. AG's Modified Mental Model of Oxygenation.



In this elaborated model, oxygen now travels through the pulmonary artery from the lungs to the heart, but oxygenation still occurs in the heart. Thus her model has not lost its basic flaw.

This first change in the model illustrates a problem with assimilating new ideas into a faulty model. While the function assigned to the pulmonary artery is consistent with her mental model, it is exactly wrong: the pulmonary artery carries blood from the heart to the lungs, not the other way around.

The second addition to the model is the heart's correct function. When AG encounters a statement about the heart pumping in the text ("The heart is a muscular organ that pumps blood through the body."), she simply adds this function to her model, without removing the other function. So she states that the purpose of the heart "is to pump blood through the body" but also that blood returning to the heart, "comes back to refill with oxygen."

The third change adds the function of oxygenation to the lungs. When AG encounters this information ("In the lungs, carbon dioxide leaves the circulating blood and oxygen enters it."), it is easily incorporated into her model. She states,

The lungs replenish the blood with oxygen and so now you have a high concentrate of oxygen in the blood.

And later:

[Blood is] going to the lungs to get oxygen. So it would have a high concentration of carbon dioxide and a lower concentration of oxygen and it would go to the lungs to get, um, oxygen.

Her model now includes oxygenation in the lungs. However, she continues to retain in her mental model that oxygenation occurs in the heart as well. For example, a little later in the readings she states that the blood "goes to the heart to get cleaned." While this misconception is not immediately removed by the addition of correct information to her model, it is weakened. The frequency with which AG refers to oxygenation in the heart declines gradually over the course of the protocol. At the same time, the ideas of pumping in the heart, and oxygenation in the lungs, are reinforced by the text, so they are referred to with increasing frequency.

In the following passages, AG talks about oxygenation in the lungs and the transportation of oxygenated blood to the heart. It is interesting to note that the misconception of oxygen traveling from the lungs to the heart in the pulmonary artery is completely absent, because it has been directly contradicted by the text, which states, "The pulmonary artery is the only artery that carries deoxygenated blood." She responds:

Um, it just says that the pulmonary artery is the only artery in the body that carries blood that has no oxygen in it.

...the blood that comes, um, into, from the heart to the lungs is not gonna have oxygen 'cause that's why it's going to the lungs. It's going to the lungs to get oxygen.

And later, responding to information about the pulmonary veins.:

The pulmonary veins are to take the new clean oxygenated blood back to the heart to be spread into the body for its use.

As these passages suggest, the initial misconception eventually fades completely, and is replaced by the correct conceptions. Evidence of her corrected model is shown best in her answer to this question in the post-test: "Does blood change in any way as it passes through the heart?"

> *Um, it changes as, when it goes into the heart it goes into the lungs, it gets oxygen, comes back into the heart, but...*
>
> *...In the heart itself...no, when it comes into the heart the first time it's deoxygenated, when it comes back in it's oxygenated. But, in the heart itself it doesn't really change.*

In that answer, we see that blood does not get oxygen in the heart, and thus AG's initial misconception has been removed through the gradual process of replacement by correct information.

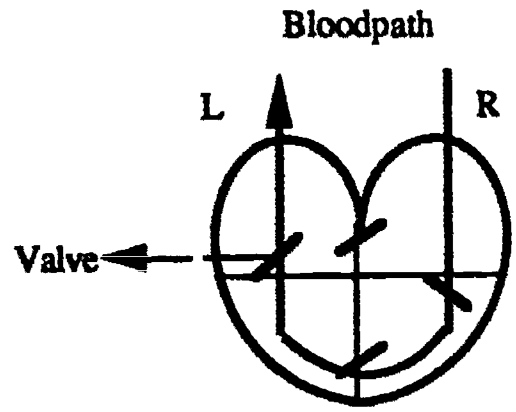
Removal of Misconceptions.

As we conjectured, misconceptions were not difficult to be removed if they were explicitly stated in the text. Let us take AG's understanding about the bloodpath in the heart as an example. In the pre-test, AG described the bloodpath in the heart as a "U-turn" shape rather than two one-way channels from the top to the bottom of the heart to pass the blood out to the body. This incorrect model has to do with her understanding about the structure of the heart which has a valve between each chamber. During the text reading, she encountered correct information in the text which provides an opportunity for her to modify her understanding to a correct representation. The following excerpts show the process of learning through the study.

Initially, AG believes that the four chambers in the heart are divided by valves and the bloodpath goes like a "U-turn" shape in the heart (See Figure 5).

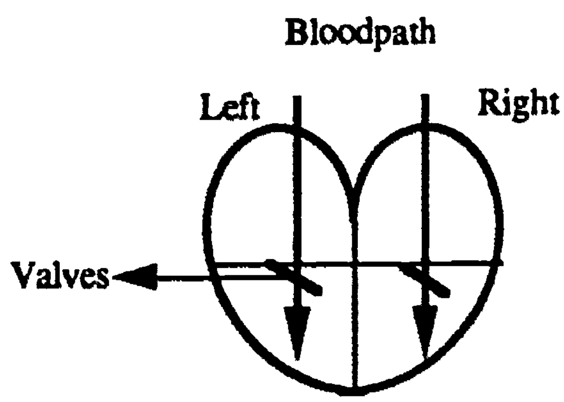
> p.18 *"it [heart] has 4 chambers... The blood goes in at the upper right chamber and it then it goes down to the umm... downward right chamber, then it goes to the downward left chamber then it goes to the upward chamber then it goes out of the body. And each chamber is divided by a valve that makes sure the blood goes in one direction"*

Figure 5. AG's Initial Mental Model about the Bloodpath in the Heart.



When she encountered correct information in the text AG completely changed her understanding about the bloodpath and the structure of the heart. This change occurred promptly, because the text explicitly and directly describes the correct bloodpath. The correct bloodpath is not compatible with her misconception, so AG abandoned her mental model without any hesitation. For instance, she reads; "In each side of the heart blood flows from the atrium to the ventricle." To which she responds; "... blood flows from top to bottom." (See Figure 6). After this direct challenge, she no longer refers to blood flowing the wrong direction on the left side of the heart. There is no evidence for persistence of the at misconception at all.

Figure 6. AG's Final Mental Model about the Bloodpath in the Heart.



There is abundant evidence to validate that she did subsequently understand the correct path. For example, at the beginning of the post-test she states:

p.249 " ... *[blood] goes through the lungs, comes back at the left atrium and goes down to* *the ventricle and then goes to the body.."*

And later:

p.251 *"The septum ..breaks up the heart into two sections...the right section and the left section. Um, and it's not allowed the right part of the heart to mix with the left part of the heart."*

Such an accurate model also has a functional significance in the circulatory system as a whole. First, the parallel flows prevent the oxygenated blood on the right from mixing with the deoxygenated blood left. Second, each flow serves the entire system with different purpose, pulmonary and systemic circulation respectively. As long as AG recognized this significance, her understanding of the bloodpath is presumably reinforced. The following conversation supports that she has understood this functional significance.

p.131

AG: "Um,... after it's [blood] in the atrium it has to go somewhere and it's gonna go down to the lower ventricle and there's, and what separates them so the blood won't run freely is the bicuspid valve. And can I answer a question now that you asked me before and I didn't know the answer to?

E: Mm-hmm.

AG: You asked me before why is it so important that the blood doesn't mix from the right side to the left side.

E: Mm-hmm.

AG: And now I know the answer. The reason is because the blood on the left side has, is still, it's not clean, it doesn't have, it has more carbon dioxide than oxygen. And the blood on, the blood on the right side has this, and the blood on the left side already has the oxygen in it and if the two mixed, you know, it would just be, you'd be..instead of having clean blood coming back to the body you'd have blood filled with carbon dioxide and you don't want that, that's why, you have to keep them separate..."

AG's misconception about the bloodpath was easily removed. There are two reasons for this finding. First, her incorrect model is not compatible with the information given in the text.

So there was no reason to persist in her misconception. Second, her incorrect mental model would not function as the correct bloodpath described in the text. With this inconsistence, AG needs to abandon her misconceptions and replace it with the functional bloodpath from the materials. In sum, misconception was not persistent when it is unambiguously confronted by the text.

Coherence. One possible contribution to the differences among students in how successfully they build a complete and correct mental model, thereby effecting how successfully they remove misconceptions, may be the way they built their understanding while reading the text. One way to capture this is to devise a method to capture the coherence of their mental model-building while reading, as well as the frequency with which they generated inferences. We captured this by identifying the frequency with which a student referenced previous sentences while explaining a current sentence that she is reading. Using such an analysis, we found that a Hi-ability student (NA) built a total of 56 links. A Low-ability student (AG), on the other hand, built only a total of 24 links. This analysis will be extended to all the students.

Conclusion

This research explores the moment-by-moment understanding students exhibit in the learning of a non-physical science domain--the human circulatory system. Our approach was to understand how students learn by capturing the nature of their initial mental models (naive conceptions), see how new information gets assimilated into their mental models, and how their mental models get revised in order to achieve the correct conception. Such an analysis informs us of the exact conditions under which misconceptions can be removed, or the conditions under which they remain.

As many other studies in the conceptual change tradition, this study reveals how certain misconceptions are robust and persistent in learning human circulatory system. However, more importantly, this study depicts that middle school students are capable of understanding some important aspects of the circulatory system and then modify their existing misconceptions with better and more coherent views.

Three major results are found. First, there is a fundamental difference between the physical and the non-physical sciences in terms of how they are learned. That is, misconceptions held historically by medieval scientists are not widely shared by contemporary students in learning the human circulatory system. Moreover, those that are shared by contemporary students are largely removed and modified by instruction. In contrast, research in physics show that misconceptions are persistent, robust, and difficult to overcome by either instruction or confrontation. Such differences support our conjecture about conceptual change requiring an ontological shift in one domain and not the other domain.

Second, aside from historically held misconceptions which we have identified a priori and formulated into questions, our analyses also reveal each individual student's unique set of misconceptions. The students are ready to abandon these misconceptions when they directly confront text materials which either contradict or challenge their incorrect or incomplete models. On the other hand, new information is assimilated to their mental models when the incoming knowledge does not directly contradict their conceptual representations. This finding supports our conjecture that confrontations which are directed at a student's mental model will be effective at achieving revisions and removal of misconceptions, whereas the methodological approach in the literature often directs the challenge at the outcomes or predictions students make from their mental models.

Third, we found that all 10 students learned this material and although there is a significant difference in the range of the gain scores across the 10 students, such difference was not a function of ability, as measured by the CAT score. This suggests that an instructional intervention such as prompting for self-explanation may be an effective heuristic for students to use in learning from text and from examples, as found in Chi, Bassok, Lewis, Reimann and Glaser (1989). However, we need to run a control group in which students are not prompted for self-explanations before we can completely confirm this interpretation.

References

Andrews, W. A., Purcell, N. J., Balconi, D.A., Davies, N. D., & Moore, D. K. (1980). *Biological Science: An introductory study.* Scarborough, Canada: Prentice-Hall of Canada.

Arnaudin, M. W., & Mintzes, J. J. (1985). Students' alternative conceptions of the human circulatory system: A cross-age study. *Science Education, 69,* 723-733.

Ausubel, D. P. (1968). *Educational psychology: A cognitive view.* New York: Holt, Rinehart & Winston.

Brewer, W. F. & Nakamura, G. V. (1984). The nature and function of schemas. In R. S. Wyer, Jr. and T. K. Srull (Eds.) *Handbook of Social Cognition.* Vol. 1. Hillsdale, N.J. : Erlbaum. pp.119-160.

Bransford, J. D. (1979). *Human cognition: Learning, understanding and remembering.* Belmont, CA: Wadsworth.

Bransford, J. D., Arbitman-Smith, R., Stein, B. S., & Vye, N. J., (1985). Analysis-Improving thinking and learning skills: An analysis of three approaches. In J. W. Segal, S. F. Chipman, and R. Glaser, *Thinking and learning skills: Vol. 1. Relating instruction to research.* Hillsdale, NJ: Erlbaum. (pp. 133-206).

Bransford, J. D. & Johnson, M. K. (1973). Considerations of some problems of comprehension. In W. G. Chase (Ed.), *Visual information processing.* New York: Academic Press. pp. 383-438.

Bransford, J. D. , Stein, B. S., Shelton, T. S., & Owings, R. A. (1981). Cognition and adaptation: The importance of learning to learn. In J. H. Harvey (Ed.), *Cognition, social behavior and the environment.* Hillsdale, N.J.: Erlbaum. pp. 93-110.

Bransford, J. D., Stein, B. S., Vye, N. J., Franks, J.J., Auble, P. M., Mezynshi, K. J., and Perfetto, G. A. (1982). Differences in approaches to learning: An overview. *Journal of Experimental Psychology: General, 111,* 390-398.

Champagne, A., Klopfer, L., & Gunstone, R. F. (1982). Cognitive research and the design of science instruction. *Educational Psychologist, 17,* 31-53.??

Chi, M. T. H. (In press). Conceptual change across ontological categories: Implications for learning and discovery in sciences. In R. Giere (Ed.), *Cognitive models of Science: Minnesota Studies in the Philosophy of Science,* University of Minnesota Press.

Chi, M. T. H., Bassok, M., Lewis, M., Reimann, P., & Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science, 13,* 145-182.

Greeno, J. G. (1977). Processes of understanding in problem solving. In N. J. Castellan, D. B. Pisoni, & G. R. Potts (Eds.) *Cognitive Theory.* Hillsdale, NJ: Erlbaum. Vol. 2, pp. 43-83.

Haugeland, J. (1978). The nature and plausibility of cognitivism. *Behavioral and Brain Sciences, 2,* 215-260.

Johnston, K. S., (1985, May/June). *Science Books and Films, 20,* 245-286.

Johnston, K. S., (1988, March/April).*Science Books and Films, 23,* 200-220.

Karplus, R., and Stage, E. K. (1981). *Misconceptions in science: Past and present approaches.* Berkeley, CA: University of California, Lawrence Hall of Science.

Kormondy, E.J. and Essenfeld, B. E. (1988). *Biology: A systems approach.* Menlo Park, CA: Addison-Wessley.

Law, N., & Ki, W. W. (1987). *A.I. programming environment as a knowledge elicitation and cognitive modelling tool.* Presented at the Third International Conference on A.I. and

Education. Pittsburgh, PA.
McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A.L. Stevens (Eds.) *Mental Models* . Hillsdale, NJ: Lawrence Erlbaum Associates. pp. 299-322.
Nersessian, N. J. (1987). Conceptual change in physics and in students of physics: From impetus to inertia. Unpublished manuscript, Princeton University.
Osborne, R. J. (1982). Science education. Where do we start? *Australian Science Teachers Journal,* 28, 21-30.
Osborne, R. J., & Wittrock, M. C. (1983). Learning science: A generative process. *Science Education, 67,* 489-508.
Reiner, M., Chi, M. T. H., & Resnick, L. (1988). *Naive materialistic belief: An underlying epistemological commitment.* Proceedings of the Tenth Annual Conference of the Cognitive Science Society, pp. 544-551. Hillsdale, NJ: Erlbaum.
Rothman, R. (1988). Panelists flay biology curriculum as outdated, filled with factlets. *Education Week* , October 9, p. 5.
Stead, B. F. & Osborne, R. J. (1980). Exploring science students's concepts of light. *Australian Science Teachers Journal, 26,* 84-90.
Stewart, J. H. (1982). Difficulties experienced by high school students when learning basic Mendelian genetics. *The American Biology Teacher, 44,* 80-84.
Tasker, C. R.(1981). Children's view and classroom experiences. *Australian Science Teachers Journal, 27,* 51-57.
Towle, A. (1989). *Modern Biology.* New York: Holt, Rinehart and Winston.
Vosniadou, S., & Brewer, W. F. (1987). Theories of knowledge restructuring in development. *Review of Educational Research., 57,* 51-67.
Weinstein, C. E. (1978). Elaboration skills as a learning strategy. In H. F. O'Neill, Jr. (Ed.), *Learning Strategies.* New York: Academic Press. pp. 31-55.