

Introduction to the Psychology of Science Text Comprehension

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Introduction to the Psychology of Science Text Comprehension

It is hardly a secret that students find most science texts very difficult to comprehend and that there are several reasons for these difficulties. The text is loaded with technical terms that need to be deciphered and memorized. There are complex mechanisms with multiple components, attributes of components, relations between components, and dynamic processes that flow throughout the system. Scientists frequently use a mathematical language, with symbols and formulae that are difficult to ground in everyday experience and that often require extreme precision. It is virtually impossible to form a mental image of some of the mechanisms without distorting the integrity of the system. Moreover, textbook authors often do not provide enough cues for readers to create coherent representations of information in science texts.

The problems are especially important for readers with poor scientific knowledge. In fact, all of the difficulties are exacerbated by the fact that most students have minimal background knowledge about science and therefore need to build an understanding nearly from scratch. Or, alternatively, they have incorrect knowledge that interferes with the scientific concepts and principles presented in textbooks. And of course, the complexity of scientific theories is increasing dramatically, year by year. As a consequence of all this, students frequently develop negative epistemic attitudes toward science texts and think of them as containing incomprehensible information. These attitudes negatively influence their text processing strategies, in a continuing downward spiral.

All of these difficulties explain why reading science textbooks is difficult and why it has become difficult to entice students to major in science. The process of learning

science is a challenge. Reading scientific text is a struggle that takes effort and concentration. Science texts are not a quick read.

School systems have periodically tried to meet the challenge by adopting radical pedagogical approaches. For example, the “physics first” approach reverses the order in which the different sciences are delivered in the school curriculum. The traditional order has been biology, then chemistry, then physics. The reason for this ordering allegedly is that biology has a high load on memory, but few exceptionally difficult conceptualizations that require a high IQ to master. So students keep busy memorizing parts of the anatomy and detailed taxonomies of animals and plants with exotic, lengthy Latin expressions. The utility of mastering precise genus and species labels is not exactly obvious and is rarely integrated with a deeper understanding of biology, but it does have a good side effect of promoting memorization and organization skills. Most of the fundamental mechanisms in biology are easier to grasp than those mechanisms in the sister sciences, so it makes sense to place biology earlier in the curriculum. In contrast, physics has the opposite profile: It is low on memorization and its key conceptualizations are difficult to master. Therefore, physics should come late. The problem with this curriculum plan is that students with a talent for science get turned off by all of the memorization in biology. A good scientific mind prefers to ask questions, generate hypotheses, play “what-if” games, experiment, test hypotheses, struggle with conflicting results, and become engaged in a host of other forms of reasoning and problem solving. Many scientific minds get turned off by a heavy dose of memorization, so unfortunately they never go into science. The “physics first” approach tries to fix this problem by reversing the order of sciences in the curriculum: physics, then chemistry, then biology.

So students quickly get started with a physics lab where they can experiment and build an inquiring scientific mind. The essence of the scientific mind is cultivated early and is not clouded by a horrendous exercise of memorization. The effectiveness of the physics first approach is currently being evaluated, but some reports suggest that it significantly increases the number of science majors.

Another radical method of pedagogy has entirely discontinued science textbooks in the classroom and laboratories. The vision is to get the students to actively experiment in the laboratory, to build inquiring minds, and not to have them accept the textbook knowledge as gospel. This “delete the textbook” approach is perhaps more appealing when literacy levels are extremely low and the quality of textbooks is extremely poor. However, many researchers have been skeptical of the removal of the textbook from the science curriculum. There are times when students need to spend hours concentrating on textbook content until they master the difficult core concepts and mechanisms in a science, without getting distracted by the mundane practices of assembling equipment, collecting observations, and recording numbers in tables and charts. The key challenge is to arrange the learning environment so that the right text is available to the right student at the right time.

Nevertheless, the primary inspiration of this edited book does not really lie in the arena of science curriculum reform. Most of the authors in this book are researchers in cognitive science, discourse processing, and education who are building models of text comprehension. Our goal is to understand how children and adults construct meaning representations while they read and study texts. We develop theoretical models of the comprehension process and test the predictions of the model by collecting empirical data

from readers. Some of the data tap the process of comprehension while text is read on-line (i.e., during reading). Examples of on-line measures include think aloud protocols, sentence reading times, the time to name test words aloud, and the timing and patterns of eye movements. Other data involve off-line measures that tap the result of comprehension, several minutes, hours, or days after comprehension is finished. Examples of off-line measures are recall tests, recognition tests on words or sentences, summaries of texts, question answering, and ratings of the importance of text constituents. A good theoretical model of comprehension can accurately account for rich patterns of data that include both on-line and off-line measures.

There are several reasons why science texts have attracted the attention of the comprehension researchers in this volume. One salient reason is that we can investigate comprehension under conditions in which comprehension is extremely difficult. As discussed above, scientific texts are difficult to understand at a deep level so these texts provide an interesting test case when the challenges of comprehension are pushed to the limit. Early research on comprehension focused on folktales, stories, everyday scripts, and other forms of narrative discourse that are easy to comprehend -- the other end of the continuum on comprehension difficulty (Bruner, 1986; Graesser, Singer, & Trabasso, 1994; Mandler, 1984; Schank, 1999). Narrative is easy to comprehend because the content is very similar to the setting, actions, events, and social world we experience in everyday life. However, researchers in discourse comprehension have advocated moving from an emphasis on the study of narratives towards programmatic research on exposition (Lorch & Van den Broek, 1997). That includes the development of theories of the structure and processing of science texts.

A second reason to study scientific texts is that there are more individual differences in comprehension processes among readers. Readers dramatically vary in their knowledge of the subject matter, their cognitive strategies of coping with exceptionally difficult content, their criteria in what it means to comprehend, and their motivation to persevere in mastering the science content. A good comprehension of scientific discourse fundamentally requires an excellent domain of highly specialized language, discourse, and world knowledge (Lemke, 1990; McKeown, Beck, Sinatra, & Loxterman, 1992; Means & Voss, 1985). In contrast, there is more uniformity among adult readers when they comprehend narrative text, at least narratives that do not have sophisticated literary forms (Graesser, Kessler, Kreuz, & McLain-Allen, 1998).

A third reason for investigating science texts is that the content of the material is useful for the readers to master. The content is not arbitrary or trivial, as in the case of much of the text materials that are written by experimental psychologists. Promoting science education fits a mission this is prominent in virtually all countries and cultures. Science textbooks have obviously played an important role in this endeavour. Yager (1983) reported that over 90% of all science teachers in the U.S. used a textbook 95% of the time. The importance of textbooks as a component of science instruction has also been advocated by other researchers (Chiapetta, Sethna, & Fillman, 1991; Gottfried & Kyle, 1992; Yore, 1991), in spite of the trend to minimize textbooks in some circles in science education.

A fourth reason for studying scientific text is because this genre of text has a distinctive way of organizing and explaining material. It is frequently assumed that coherence and comprehension are closely related. Under most, but not all circumstances,

a coherently organized text facilitates the readers' comprehension and subsequent task performance. However, sometimes the text *per se* is not sufficient for conveying the complex systems in mechanical, biological or physical systems. The text needs to be enriched by adjunct illustrations, diagrams, tables, figures, photographs, and so on. Furthermore, in this electronic age, there is multimedia, hypermedia, simulation, and other computer technologies that allegedly facilitate more active learning and hopefully deeper comprehension. However, there is very little empirical research on the effectiveness of these nontextual technologies, so this is an important direction for future research.

What is a Science Text?

We are intentionally going to define science text very broadly in this volume. There will be a broad definition of science and a broad definition of what falls under the umbrella of a scientific text genre. Regarding a definition of science, we adopt the natural category that is recognized in the National Science Foundation as SMET, which stands for Science, Mathematics, Engineering, and Technology. Our definition is compatible with Parker's definition in the *Concise Encyclopedia of Science and Technology* (1994):

Science ... is characterized by the possibility of making precise statements which are susceptible of some sort of check or proof. This often implies that the situations with which the special science is concerned can be made to recur in order to submit themselves to check, although this is by no means always the case. There are observational sciences such as astronomy or geology in which

repetition of a situation at will is intrinsically impossible, and the possible precision is limited to precision of description (p. 1661).

According to Parker, technology is a part of science, as described below:

Technology is a systematic knowledge and action, usually of industrial processes but applicable to any recurrent activity. Technology is closely related to science and to engineering. Science deals with humans' understanding of the real world about them –the inherent properties of space, matter, energy, and their interactions. Engineering is the application of objective knowledge to the creation of plans, designs, and means for achieving desired objectives. Technology deals with the tools and techniques for carrying out the plans (p.1876).

The status of mathematics is perhaps on the edge of these definitions and will not be directly addressed in this edited volume. However, all forms of science, engineering, and technology embrace some form of mathematics, which perhaps explains its inclusion in the SMET program of the National Science Foundation.

Our definition of the scientific text genre embraces several rhetorical forms and media. There are academic textbooks, scientific journal articles, technical manuals, magazine and newspaper reports tailored for the general public, information brochures for the public, and electronic multimedia on the web and CD-ROM. The material is prepared by the author with the primary role of the diffusion of new knowledge about science. The chapter in this volume by Goldman and Bisanz presents a large landscape of science texts and their discourse functions. The chapter by Chambliss describes a theoretical framework for designing textbooks that integrate curriculum, instruction, and comprehensibility. Nearly all science texts are in the expository genre because they are

written to explain and describe to the reader new content that has a foundation in truth and/or empirical evidence. However, some forms have a layer of persuasion, such as when a researcher is arguing with colleagues that a particular scientific claim is true or a particular scientific theory has merit. Scientific texts may also be in the narrative genre, as in the case of science history. It is widely acknowledged that many texts do not crisply fall into the traditional genre umbrellas of exposition, persuasion, narrative, and description (Brooks & Warren, 1972).

The Representation and Processing of Scientific Text

The content of scientific texts has multiple levels of representation, but the most important split is between shallow and deep knowledge. Shallow knowledge consists of explicitly mentioned ideas in a text that refer to: lists of concepts, a handful of simple facts or properties of each concept, simple definitions of key terms, and major steps in a procedure (not the detailed steps). Deep knowledge consists of coherent explanations of the material that fortify the learner for generating inferences, solving problems, making decisions, integrating ideas, synthesizing new ideas, decomposing ideas into subparts, forecasting future occurrences in a system, and applying knowledge to practical situations. Deep knowledge is presumably needed to articulate and manipulate symbols, formal expressions, and quantities, although some individuals can master these skills after extensive practice without deep mastery. Deep knowledge is essential for handling challenges and obstacles because there is a need to understand how mechanisms work and to generate and implement novel plans. Explanations are central to deep knowledge, whether the explanations consist of logical justifications, causal networks, or goal-plan-action hierarchies. It is well documented that the construction of coherent explanations is

a robust predictor of an adult's ability to learn technical material from written texts (Chi, deLeeuw, Chiu, & LaVancher, 1994; Cote, Goldman, & Saul, 1998; Graesser, VanLehn, Rose, Jordan, & Harter, in press; Webb, Troper, & Fall, 1995). Some of the chapters in this volume directly address the processes and challenges of constructing coherent explanations of the material (see León & Peñalba; Mayer; Ohlsson).

The representations of texts and pictures can be segregated into the levels of surface code, explicit propositions, mental models, and pragmatic interaction (Graesser, Millis, & Zwaan, 1997; Kintsch, 1998). The most shallow level is the surface code, which preserves the exact wording and syntax of the explicit verbal material. When considering the visual modality, it preserves the low-level lines, angles, sizes, shapes, and textures of the pictures. The explicit proposition representation (often called the textbase) captures the meaning of the explicit text and the pictures. A proposition contains a predicate (main verb, adjective, connective) that interrelates one or more arguments (noun-referents, embedded propositions). Examples of propositions are *the cam is between the cylinder and the spring* [BETWEEN (cam, cylinder, spring)], *the singer repaired the computer* [repair(singer,computer)], and *if the cam rotates, the spring contracts* [IF(rotate (cam), (contract (spring))]. At the deepest level, there is the mental model (or situation model) of what the text is about. For everyday devices, this would include: the components of the electronic or mechanical system, the spatial arrangement of components, the causal chain of events when the system successfully unfolds, the mechanisms that explain each causal step, the functions of the device and device components, and the plans of agents who manipulate the system for various purposes.

Still another level of representation of scientific texts, related to the situation model but slightly different from it, has been proposed for scientific problems (Nathan, Kinstch, & Young, 1992). Good readers create a level of representation called the problem model that is built taking into account the formal (mathematical) relations that exist between the elements described in the statement of a problem. For this, a reader needs not only world knowledge, as for building a situation model, but also scientific and mathematical knowledge on the relations between the variables involved in the problem statement. Thus, a student may create an appropriate situation model corresponding to the text that describes a scientific problem, for example, one involving a person sliding down an hemispheric dome. However, the student still be incapable of translating this into scientific concepts and principles, i.e., building the problem model. That is, the student may be unable to represent the situation in terms of the variables and relations needed to describe position and velocity, the forces acting on the person, the types of energy change involved, and the relations among all of the various components.

Finally, there is the pragmatic communication level that specifies the main messages that the author is trying to convey to the reader (or the narrator to the audience). Examples of purposes of reading are to explain how to repair equipment, to advertise a product, or to protect someone from a hazardous condition.

The types of representations are theoretically different from the levels. From the present standpoint, there are several types of knowledge representation affiliated with the explicit propositions and mental models that underlie science texts. Table 1 lists some important types of knowledge representations that are prominent in science (Graesser, Gordon, & Brainerd, 1992). Each of these types of knowledge become progressively

deeper to the extent that they are more fine-grained (i.e., the grain size has high resolution) and have more complex interconnections among subcomponents (i.e., there are more relational links and more links that deviate from a strict hierarchy).

Cognitive processes also vary in difficulty. Table 2 lists the major types of cognitive processes that were proposed by Bloom (1956) and others nearly 50 years ago. According to Bloom's taxonomy of cognitive objectives, the cognitive processes with higher numbers are more difficult and require greater depth. Recognition and recall are the easiest, comprehension is intermediate, and classes 4-7 are the most difficult. It is debatable whether there are differences in difficulty among categories 4-7, so they are often collapsed into one category in most applications of this taxonomy.

The representations and processes in Table 2 do not cover all of the theoretical distinctions that are embraced by today's comprehension researchers. As one would expect from any scientific enterprise, the researchers have dissected the representations and processes in rich detail. For example, researchers have contrasted the different memories that operate during comprehension. There are the distinctions between short-term memory (STM), working memory (WM), and long-term memory (LTM), which are quite familiar to anyone who has taken an introductory course in cognitive psychology. Ericsson and Kintsch (1995) have recently added a layer of complexity by introducing the notion of a long-term-working memory (LT-WM). The contents of STM at any point in time may trigger processing skills in LTM that quickly fetches additional content in LTM. Thus, a person who is highly skilled in memory retrieval for a particular subject matter (e.g., an expert in botany) would appear to have a larger WM for scientific texts on botany because of the expert retrieval skills in LTM for botany. The chapter by

Tapiero and Otero reports that this added expertise in a subject matter, and the associated LT-WM, allows the reader to build richer situation models and more globally coherent text representations. In contrast, these advantages in subject matter expertise cannot be explained by the propositional textbase level.

As another example, comprehension researchers have vigorously investigated the process of constructing knowledge-based inferences during the comprehension of scientific texts (Cote et al., 1998; Graesser & Bertus, 1998). Some of the important classes of inferences are presented in Table 3. The inferences in Table 3 do not exhaust the classes of inferences that comprehension researchers have investigated (see Graesser et al., 1994, for a more complete inference taxonomy), but they do cover the inferences investigated by the authors of this volume. For example, Maury, Perez, and Leon investigated the extent to which predictive inferences and goal inferences are constrained by the verbs in the explicit events being read. Leon and Penalba compare the explanation-based causal inferences that get constructed in scientific text versus narrative text. Ohlsson proposes that explanations in science are constructed from an assembly of generative relations and explanation schemas. He demonstrates how this is done by analyzing a corpus of naive explanations in the domain of evolutionary biology.

Inferences play a particularly important role in creating coherence in the representations of science texts. Some scientific genres, like those addressed to experts, take for granted an important inferencing activity of readers to fill many deliberate coherence gaps in the explicit textbase. This style is sometimes inappropriately carried over to educational texts. When it happens, it places a large burden on readers who are expected to make inferences, without the fortification of expert world knowledge. Such

inferences can only be made by the more able students. Sometimes it is beneficial for knowledgeable readers to receive texts with coherence gaps, and to expect them to fill the gaps with inferences (MacNamara, Kintsch, E., Songer, & Kintsch, W., 1996). However, texts with coherence gaps are detrimental for most readers because of the limitations in their knowledge and processing strategies.

The extent to which readers generate inferences depends on the reader's standards for what it means to comprehend something. Some readers demand a deep comprehension of the material, particularly if they have high subject matter knowledge, high standards, and/or high motivation. Other readers settle for a shallow representation that glosses over potential contradictions within the text and between the text and world knowledge. The process of comprehension monitoring determines the depth of comprehension, whether discrepancies or gaps in understanding are detected, and whether readers repair these problems appropriately. These metacognitive regulatory processes are addressed in several chapters in the volume. Dunlosky, Rawson, and Hacker propose that comprehension disruptions may occur at different levels of text representation and that rereading a text has the benefit of addressing more disruption at the deeper mental model. Otero analyzes the regulatory processes that occur when readers find inconsistencies in science texts and attempt to repair the problems. The regulation mechanism is modeled as a constraint satisfaction process in which readers evaluate the coherence of their mental representation of a text with respect to a standard. Inferences are generated if the coherence of the text does not meet the threshold of a standard. Van Oostendorp investigates the process of updating a mental model of a scientific text when it has a clear-cut contradiction.

Deep comprehension and inferences may be facilitated by information sources other than the text *per se*. A number of chapters explored the impact of pictures, animation, questions, and other adjunct information sources on text comprehension. Martins discusses the content and functions of visual images in science textbooks. Schnotz, Bannert, and Seufert proposes a model that identifies the mental representations that are created from scientific text versus pictures, including how they are integrated and how they may differ. There are conditions in which a picture can interfere with comprehension, as in the case of simple pictures that have minimal or misleading information. Mayer has systematically investigated how words, pictures, and animations may be effectively coordinated to promote deep comprehension of various physical, mechanical, and biological systems. Hegarty, Narayanan, and Freitas designed and tested the impact of hypermedia on the construction of explanations of how mechanical systems work. Rouet and Vidal-Abarca discuss the impact of adjunct questions and the question answering process can systematically influence the comprehension of science texts. These adjunct information sources and media are expected to improve in the future, given that we are in the age of bewildering technological advances, including the electronic textbook. However, it is not necessarily true that learning is facilitated by an animation of a mechanical system, a simulation of the mechanism that the learner can interactively manipulate, and embodied exploration of the science world in virtual reality. There is no solid evidence, for example, that animation facilitates learning. Comparisons between linear text and hypertext/hypermedia are similarly unspectacular, if not disappointing.

Once again, one of the central challenges lies in the fact that most readers have very little knowledge of science as a subject matter. As a consequence, the reader is confronted with a situation in which background knowledge base is virtually bankrupt. How does the reader cope with the comprehension task when there is this serious conceptual handicap? According to the chapter by Elshout-Mohr and Daalen-Kapteijns, the reader relies on establishing local coherence at the level of the textbase, and also on the global schemata at the level of world knowledge and rhetorical structure. There is not much hope in constructing a rich mental model without the requisite background knowledge. According to Van den Broek's landscape model, the reader tries to construct a coherent meaning representation by activating incoming information, linking it to prior information, and reactivating the old explicit information in a working memory with limited capacity. The reader therefore resorts to systematically crunching on the textbase rather than incorporating many knowledge-based inferences. This, as pointed out above, results in incoherent scientific text representations, given the scarcity of explicit causal, logical, or mathematical links in scientific textbases.

The research in this book is guided by theories and models of comprehension that have dominated discourse processing, cognitive psychology, and education in recent years. When considering discourse processing, the major theoretical positions are the constructionist theory (Graesser et al., 1994), the construction-integration model (Kintsch, 1998), the memory-based resonance models (O'Brien & Myers, 1999), the landscape model (see van den Broek's chapter), and the event-indexing model (Zwaan & Radvansky, 1998). The field of education has proposed several theories that make specific predictions about what improves comprehension and memory for learning

material. These include principles of self-explanation (Chi et al., 1994), the dual code hypothesis (Paivio, 1971), and a variety of constructionist theories (Bransford, Goldman, & Vye, 1991; Moschman, 1982). The more interdisciplinary field of cognitive science has offered architectures of computation and knowledge representation that are routinely embraced by various chapters in this volume, such as conceptual graph structures with nodes and relational arcs, schema-based templates, production systems that operate on content in working memory, abstract neural networks, and constraint satisfaction mechanisms. Collectively, these models offer a rich foundation for generating discriminating predictions on patterns of empirical data, whether they involve on-line measures or off-line measures.

Organization of the Book

This book reports research on the comprehension and production of scientific texts. It is divided into four major parts. Part I (The Functions, Content, and Design of Scientific Texts) provides an overview of the different discourse genre, rhetorical formats, design features, and functions of scientific texts. This section is not limited to printed text, but includes pictures, images, animation, and various other atextual media. Part II (Basic Cognitive Representations and Processes in Text Comprehension) presents theoretical models of text comprehension, as well as empirical tests of the theoretical predictions. Part III (Comprehension Monitoring) focuses on the process of regulating comprehension, which is particularly critical in science comprehension because of the inherent difficulty of the subject matter. Comprehension monitoring is also a fundamental process indeed, but Part III is devoted to the research projects that have

focused on this critical process. Part IV (Coordinating Multiple Information Sources and Media) goes beyond the main text and incorporates adjunct sources and media.

Table 1: Important types of knowledge representation for science texts.

Class inclusion. One concept is a subtype or subclass of another concept.

For example, a *Pentium* is-a *computer* is-a *device*.

Spatial layout. Spatial relations among regions and entities in regions.

For example, a *pin* is-in a *cylinder* is-in a *lock*. A *spring* surrounds a *rod*.

Compositional structure. Components have subparts and subcomponents.

For example, a *computer* has-as-parts a *monitor*, *keyboard*, a *CPU*, and *memory*.

Procedures and plans. A sequence of steps/actions in a procedure accomplishes a goal.

An example is the steps in removing the hard drive in a computer.

Causal chains and networks. An event is caused by a sequence of events and enabling

states. An example is the sequence of events that lead to a polluted lake.

Agents. Organized sets people, organizations, countries, and complex software units.

Examples are organizational charts and client-server networks.

Others. Property descriptions, quantitative specifications, rules.

Table 2: Types of cognitive processes.

(1) **Recognition**. The process of verbatim identification of specific content (e.g., terms, facts, rules, methods, principles, procedures, objects) that was explicitly mentioned in the text.

(2) **Recall**. The process of actively retrieving from memory and producing content that was explicitly mentioned in the text.

(3) **Comprehension**. Demonstrating understanding of the text at the mental model level by generating inferences, interpreting, paraphrasing, translating, explaining, or summarizing information.

(4) **Application**. The process of applying knowledge extracted from text to a problem, situation, or case (fictitious or real-world) that was not explicitly mentioned in the text.

(5) **Analysis**. The process of decomposing elements and linking relationships between elements.

(6) **Synthesis**. The processing assembling new patterns and structures, such as constructing a novel solution to a problem or composing a novel message to an audience.

(7) **Evaluation**. The process of judging the value or effectiveness of a process, procedure, or entity, according to some criteria and standards.

Table 3. Classes of inferences that are relevant to scientific texts.

- (1) **Anaphoric references.** A pronoun or noun-phrase refers to a previous text constituent or to an entity already introduced in the mental model.
- (2) **Bridging inferences.** Any inference that is needed to semantically or conceptually relate the current sentence being read with the previous content. These are sometimes called backward inferences.
- (3) **Explanation-based inferences.** The current event being read is explained by a causal chain or network of previous events and states. These are sometimes called causal antecedent inferences.
- (4) **Predictive inferences.** The reader forecasts what events will causally unfold after the current event being read. These are sometimes called causal consequence or forward inferences.
- (5) **Goal inferences.** The readers infers that an agent has a motive that explains an intentional action.
- (6) **Elaborative inferences.** These are properties of entities, facts, and other associations that are not explained by causal mechanisms.
- (7) **Process inferences.** These inferences specify the detailed steps, manner, or dynamical characteristics of an event as it unfolds.

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