Enhancing Science Literacy for All Students With Embedded Reading Instruction and Writing-to-Learn Activities

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Reading and writing in science have been frequently maligned but infrequently studied since the 1960s move toward hands-on science. Current interest in the printed-based language arts in science is supported by contemporary educational reforms and the realization that simply doing more hands-on activities may not improve meaningful learning. Students need opportunities to consolidate their science experiences and to contrast their understandings with the interpretations of the science establishment. Science literacy means that students learn about the "big" ideas of science and how to inform and persuade others about these ideas. This article attempts to sketch a substantive framework for using science reading and science writing with deaf students based on research and informed practice with hearing students.

The prime purpose of this article is to suggest practices that will enhance science literacy for *all students.* The recommendations are made in the context of current educational reform (AAAS, 1990, 1993; NCTE/IRA, 1996; NRC, 1996), which encourages contemporary literacy that goes beyond traditional reading, writing, and arithmetic and refocuses the emphasis on dynamic literacy (Morris & Tchudi, 1996) and science instruction that emphasizes meaningful learning. This undertaking involves improving students' habits-of-mind, critical thinking, and ability to construct understanding; increasing their understanding of the "big" ideas of science (the nature of science, the practice of scientific inquiry, and the unifying concepts of science); and facilitating their communications to inform others and to persuade others to take informed action (Ford, Yore, & Anthony, 1997). Face-to-face communications and communicating at a distance are equally useful to promote and apply science literacy. Talking about science has received much emphasis, but students need to be able to read for understanding, evaluate the credibility of information sources, and produce a wide variety of written discourse (NRC, 1996, p. 36). If we wish to promote science literacy among deaf students, we must address how we can help our students become members of a language community and better communicators, especially science readers and science writers. The promising practices included here were selected for their wide applications across student ages, their integration of reading and writing, and their promotion of conceptual understanding as well as improved communications.

Based on my 35 years as a science teacher in elementary school, secondary school, and university and on my 26 years as a researcher interested in reading and writing in science, I believe we need to *do first and read and write later.* Science instruction needs to present science as inquiry, enhance students' concrete experience with science, and provide a more authentic view of science as an evaluative, connected, and dynamic enterprise. Furthermore, science instruction needs to illustrate reading and writing as interactive, constructive meaning-making processes; address metacognition as awareness and executive control of meaning making;

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and provide explicit strategy instruction on a just-in-time basis within authentic science inquiries and professional practices. Collectively, these suggestions lead toward explicit reading and writing instruction embedded in authentic science courses and professional education. A quick survey of recent science teaching journals (*Journal of College Science Teaching, Science and Children, Science Scope, Science Teacher*) revealed several articles by science professors and teachers describing innovative attempts to address print-based language arts and study skills. Professionals recognize that elementary, secondary, college, and university students need explicit help to remediate reading, writing, and study strategies in science. These explicit approaches will improve their chances of success as science students and help meet the communication demands of a science-literate person and a practicing science professional.

Limited research has outlined the potential value of print-based language in science learning (Rivard, 1994; Rivard & Yore, 1993; Rowell, 1997; Yore & Shymansky, 1985); and the common-sense and grass-roots supporters of reading and writing across the curriculum have promoted generic relationships among reading, writing, and learning. Although the relationships among reading to learn, writing to learn, and science learning are not well established, one researcher maintains that the available "research does not support the concocted claims that reading and writing in science naturally inhibit students' creativity, curiosity, and interest" (Holliday, 1992, p. 60). Unfortunately, such sweeping negative claims appear to be based in education folklore, dated research results, and antiquated perspectives of science reading and science writing and provide no productive resolution to the print-based demands of science language, accessing scientific information and communicating science discoveries. The following pages attempt to provide science teachers and professors with contemporary models of science reading and writing and strategies for using and enhancing print-based language arts in their science instruction.

Background

Some years ago I was asked to put together an agenda for reading and writing research for science educators. A summary of the available research and a reflection on my own thinking and experience led me to conclude that the dominant models of science reading and science writing did not accurately reflect the recursive nature of these print-based language arts, did not consider the unique characteristics of the science domains, misrepresented the pedagogical purposes for reading and writing in a content area, and ignored the understandings of the participants—professors, teachers, and students. Later, as co-editor with William Holliday and Donna Alvermann of a Special Issue of the *Journal of Research in Science Teaching*, our thinking was focused in the introductory article, "The Reading-Science Learning-Writing Connection: Breakthroughs, Barriers, and Promises" (Holliday, Yore, & Alvermann, 1994). We believed:

> The single most important advancement in science reading has been the parallel but independent reconceptualization of reading as an interactive-constructive process and science learning as something more than conditioned responses and rote memorization. Much early science reading research was guided by a text-driven, bottom-up model that emphasized decoding skills and textual attributes. This research encouraged controlled vocabulary, fragmented sentence structure, and reduced conceptual demands that generally de-emphasized the science curriculum and discounted the utilization of textual materials in science teaching. (p. 879)

Furthermore, we continued:

> Writing, like interactive-constructive reading, depends upon the writer's prior domain and strategic knowledge, purpose, and interest. Bereiter and Scardamalia (1987) described the interactive and constructive processes involved in the knowledge-transforming model of writing that parallels the generative model of science learning in that it involves long-term memory, working memory, and sensory-motor activity. The knowledge-transforming model appears to be far more interactive and recursive than linear. The tasks of goal-setting and text production do not fully reveal the complex cognitive, metacognitive, and memory factors involved in the retrieval of conceptual and discourse knowledge from long-term memory and the execu-

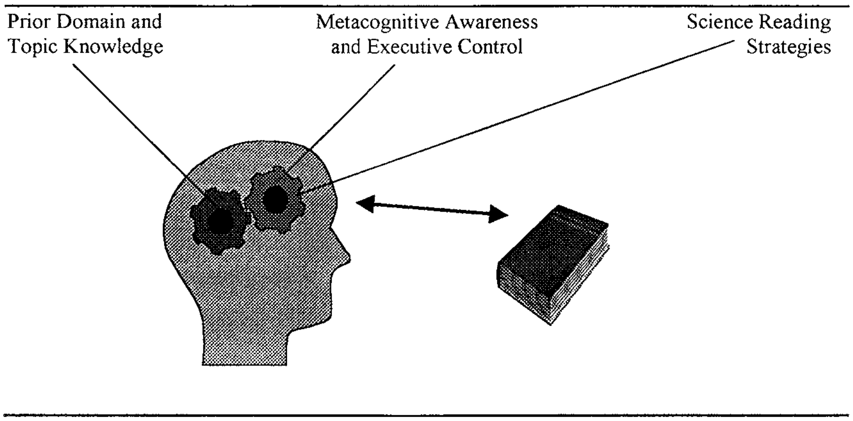

Figure 1 Interactive-constructive model of science reading: Requisite knowledge, metacognition, and strategies.

> tive control, strategic planning, and construction taking place in short-term memory. (pp. 885–886)

We were trying to dislodge the mental models of most science educators about reading and writing as skills-oriented, unidirectional, text-driven, or text-production processes. Many science educators formulated these interpretations from their early schooling that emphasized skills-and-drills language arts programs involving the unnatural language of Dick, Jane, Spot, and Puff ("Run, Spot, run," "See Dick run") and simple-minded workbooks.

We can develop much-improved images of science reading and science writing if we analyze our current authentic language uses and practices. Mallow (1991) described authentic science reading: "The scientist sits down with pencil and paper and slowly works through the article, making notes along the way. Unclear points are pondered over, references are looked up, numerical calculations are checked" (pp. 321, 331) and mental experiments are conducted. This is far different from my early reading about Dick, Jane, Spot, and Puff. Likewise, the writing of this article differs significantly from the 24-hour panic of outline, draft, and good copy process to produce 500 words (not 499 or 501 but exactly 500) that I recall from my English 11 course. I spent weeks struggling to clarify purpose and audience and questioning my own expertise and then weeks trying to achieve my earlier expectations, only to revisit and revise them as new ideas arose. As the editors' deadline approached, I faced anxiety related to making the final revisions that incorporated recent experiences, anticipated readers' pressing questions, and produced the insights missing in the earlier drafts. These paper and pencil activities were punctuated with numerous trips to the library, conversations with colleagues, and reflections (lots of reflections!).

Science Reading

Science reading is not simply a bottom-up process of taking meaning from printed symbols. Rather, science reading is an interactive-constructive process wherein the reader makes meaning by negotiating understanding among the science text and the reader's concurrent experiences and memories of the topic, science, science text conventions, and science reading procedures within a sociocultural context (Yore & Shymansky, 1991). The interactive-constructive model of science reading (Figure 1) recognizes the importance of prior knowledge, strategies, and metacognitive awareness and executive control of meaning making (Ruddell & Unrau, 1994).

Samuels (1983) stated: "[N]o longer do we think of reading as a one-way street from writer to reader, with the reader's task being to render a literal interpretation of the text" (p. 260). We have discounted the beliefs that expertise is simply the number of decoding skills acquired or that meaning is simply embedded in the text (Valencia & Pearson, 1987; Wittrock, Marks, & Doctorow, 1975). Flood (1986) metaphorically described the role of printed language in the construction of understanding as the way a contractor uses blueprints in the construction of a building: "Texts establish broad limits of possible meanings, but they do not specify a single meaning. Readers (not texts) create meaning through negotiations with authors" (p. 784).

Readers progressively resolve conflicting meanings involving text-based interpretations extracted from print, the reader's episodic memory and semantic memory, and the situation's sociocultural context (van Dijk & Kintsch, 1983). Episodic memory involves stored recollections of ideas and experiences related to the central topic(s) of the message. Semantic memory involves the reader's recollections of language structures, science text, and the scientific enterprise. Sociocultural context includes the values, beliefs, opinions, and attitudes inherent in the learning environment. Osborne and Wittrock (1983) stated:

> To comprehend what we are taught verbally, or what we read, or what we find out by watching a demonstration or doing an experiment, we must invent a model or explanation for it that organizes the information selected from the experience in a way that makes sense to us, that fits our logic or real world experiences, or both. (p. 493)

A thoughtful, expert reader is a person who links existing knowledge and text-based information to make sense of text, monitors comprehension throughout the reading process, repairs comprehension if a problem is detected, identifies what is important in text, synthesizes information continuously while reading, draws inferences during and after reading, and asks questions to set purpose, access additional information, and monitor understanding (Pearson, Roehler, Dole, & Duffy, 1992). Expert science readers use their collection of strategies in a flexible, compensating fashion to achieve goal-directed processing and a desired purpose (Kurcan & Beck, 1997) by switching to a different strategy within the strategic cluster when one strategy does not achieve the established goal (Yore, Craig, & Maguire, 1998). Several reading strategies have been identified that were critical to the expert reader, were underdeveloped in novice readers, and responded to instruction (Dole, Duffy, Roehler, & Pearson, 1991; Pressley, Johnson, Symons, McGoldrick, & Kurita, 1989):

1. Assessing the importance of text-based information and prior knowledge,
2. Generating questions to set purpose,
3. Summarizing,
4. Inferring meaning,
5. Monitoring comprehension,
6. Utilizing text structure,
7. Reading and reasoning critically,
8. Improving memory,
9. Self-regulating to fix comprehension failures, and
10. Skimming, elaborating, and sequencing.

Kurcan and Beck (1997) stressed that strategy instruction should not be isolated or focused on a discrete strategy, but should focus on the readers' "efforts to make sense of ideas or build their understanding . . . [in] a constructivist orientation" (p. 285).

Making meaning is coordinated by the readers' metacognition—awareness and executive control (Garner, 1994). Jacobs and Paris (1987) suggested that metacognition is the conscious self-appraisal (awareness) of one's own knowledge of task, topic, and thinking, and the conscious self-management (executive control) of the related cognitive processes (Figure 2). They believed that both self-appraisal and self-management could be subdivided into three separate components, whereas others believe awareness and executive control are two unified clusters. Self-appraisal (metacognitive awareness) becomes knowing *what* strategy, knowing *how* to perform the strategy, and knowing *when* and *why* to use the strategy. Self-management (executive control) becomes the *planful* setting of purpose, accessing prior knowledge, selecting appropriate strategies, and outlining a heuristic; the continuous *monitoring* of progress by checking, self-questioning, and comparing; and the *adjusting* of action by seeking external help, using a new problem-solving approach, and selecting a different strategy.

Recent explorations of middle-year students (grades 4–8) revealed that their metacognitive awareness of science reading, science text, and science reading strategies was not fully developed, that metacognitive awareness influenced science achievement, and that explicit comprehension instruction improved metacognitive awareness and science reading comprehension. Results from a 63-item Index of Science Reading Awareness on 532 students and follow-up interviews of a 10% subsample revealed that the middle-

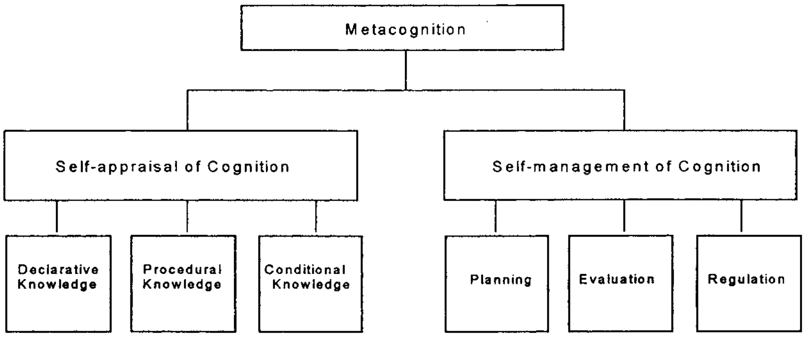

Figure 2 Metacognition (Jacobs & Paris, 1987).

year students' metacognitive awareness of science reading, text, and strategies was much like the metacognitive awareness of younger elementary school students of narrative reading, text, and strategies (Yore, Craig, & Maguire, 1998). Girls and students judged to be above average in language arts had significantly higher metacognitive awareness than boys and students judged to be below average in language arts. Examination of declarative, procedural, and conditional knowledge revealed that conditional knowledge was not always the least developed component and metacognitive awareness did not exist as three distinct components (Craig & Yore, 1995, 1996). Furthermore, students had an absolute, authoritarian perspective of science text, were bound by print, and utilized a limited repertoire of strategies. Holden and Yore (1996) demonstrated that metacognitive awareness had positive influences on science learning (grades 6–7); while Spence, Yore, and Williams (1999) demonstrated that explicit strategy instruction embedded in inquiry-oriented science teaching could improve grade 7 students' science reading metacognitive awareness and science reading comprehension.

Collectively, the generic and science reading research support the following desired image of a successful science reader (Yore, Craig, & Maguire, 1998). An effective science reader:

- realizes that *science reading* is an interactive-constructive process involving the reader, the text, and the context and is designed to make meaning of print rather than take meaning from text by integrating prior knowledge, concurrent experience, and text-based information;
- has the abilities, self-confidence, and self-efficacy necessary for *science reading* as an assigned task and for personal pleasure;
- operates at the automatic level when *science reading* is proceeding successfully, but shifts to conscious, deliberate approaches when reading comprehension is difficult or the task's demands dictate;
- realizes that science words are labels for ideas, science ideas are based on experiences, and *science text* is stored descriptions and explanations of ideas, events, or patterns;
- realizes that science is people's attempt to search out, describe, and explain patterns of events in the universe, that *science text* is not an absolute truth, and that *science text* is a form of interpretation of ideas resulting from the scientific enterprise;
- evaluates *science text* for plausibility, completeness, and interconnectedness by verifying the textual message against prior knowledge, evidence, and observed reality and by assessing the logic and plausible reasoning of the text's patterns of argumentation;
- identifies purpose of science reading, accesses prior knowledge, plans heuristics, and selects appropriate *strategies;*
- uses specific knowledge-retrieval *strategies* to access prior domain and topical knowledge from long-term memory;
- uses specific knowledge input *strategies* to access text-based information from print and visual adjuncts and to access information from the context

- uses knowledge-constructing *strategies* to integrate new information and established knowledge structures, to reorganize knowledge structures to accommodate discrepant information, to negotiate understanding, and to establish importance;
- applies critical thinking *strategies* to assess validity of information and to verify constructed understanding;
- uses monitoring *strategies* to assess comprehension; and
- uses *strategies* to regulate effort, actions, and approaches to fix comprehension failure as required.

Synthesis of science learning and science reading research has asserted that students (DiGisi & Yore, 1993; Rivard & Yore, 1993; Yore & Shymansky, 1985):

- have limited strategies to address comprehension failure, with re-reading being the most common strategy used (Wandersee, 1988);
- lack judgment of importance (Dee-Lucas & Larkin, 1986, 1988a, 1988b);
- lack procedural and conditional knowledge and astuteness application of strategy (Ferguson-Hessler & de Jong, 1990);
- lack appropriate scientific knowledge to interpret text (Reif & Allen, 1992); and
- lack understanding of bilingual character (mathematical/linguistic features) of science text (Alexander & Kulikowich, 1994).

These weaknesses provide a reasonable framework on which to develop explicit science reading instruction: conceptual background; knowledge about science text and science reading; declarations, procedures, and conditions of reading strategies; and executive control to set purpose, monitor progress, and adjust actions.

Science Writing

Much of writing in science classes utilizes a knowledge-telling model of writing to evaluate students' understanding (Rivard, 1994). Students systematically select a topic, recall understanding, draft a product, and produce a final copy. Scardamalia and Bereiter (1986) encouraged teachers to help their students move from the predominant knowledge-telling writing, which involves converting knowledge from long-term memory into written words essentially unaltered, to a knowledge-transforming approach in which knowledge is actively reworked to improve understanding—"reflected upon, revised, organized, and more richly interconnected" (1986, p. 16). The knowledge-transforming model (Bereiter & Scardamalia, 1987) clarifies the role of conceptual knowledge about the nature of science and the target topics, the metacognitive knowledge about and management of written science discourse, patterns of argumentation and genre, and science writing strategies' influence on the science writing process (Figure 3).

Prior knowledge about the scientific enterprise and science topic would include (1) recognition that science is inquiry while technology is design; (2) how scientists use evidence, warrants, and claims to formulate inference chains; (3) awareness of the relationships among science, technology, society, and the environment; (4) understanding of unifying concepts of science; and (5) knowledge of specific concepts. Metacognitive awareness of written science discourse includes declarative, procedural, and conditional knowledge about the rules of the scientific/mathematical symbol system, grammar, punctuation, spelling, audience, genre, and visual adjuncts. Executive control would involve deliberate self-regulation, setting purpose, planning strategic ways to achieve the purpose, generating ideas, organizing ideas, evaluating ideas, translating ideas into text, monitoring effects, reflecting, revising, and assessing internal consistency (Ferrari, Bouffard, & Rainville, 1998; Keys, 1999). Science writing strategies include effective use of the dual nature of science language (English and mathematics), data displays, visual adjuncts, metaphors, and scientific terminology, and the alignment of genre, purpose, language, and audience. Utilizing the knowledge-transforming model as an operational framework would encourage science educators to establish conditions for discovery in which writers are challenged to synthesize divergent and discrepant experiences and information sources to produce, not reproduce, knowledge (Anthony, Johnson, & Yore, 1996; Galbraith, 1992). Students then would spend more time setting purpose, specifying audience, thinking, negotiating, strategically planning, reacting, reflecting, and revising (Holliday et al., 1994).

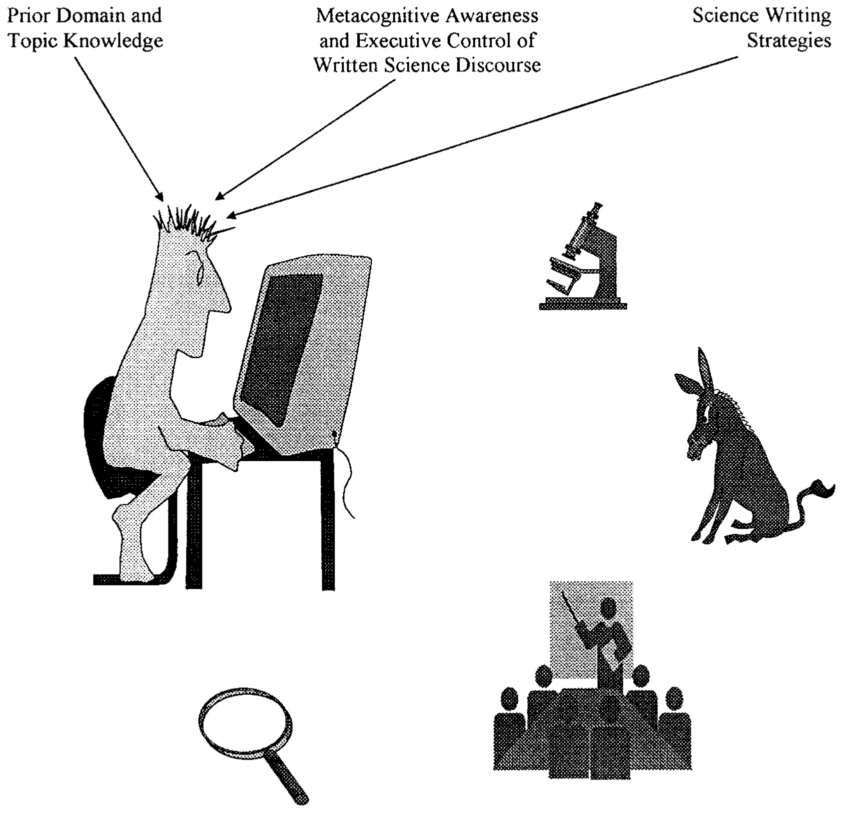

Figure 3 Knowledge-transforming model of writing (Bereiter & Scardamalia, 1987).

Explicit writing tasks and instruction embedded in the authentic context of scientific inquiry should be provided as an integral part of science courses (Hand, Prain, Lawrence, & Yore, in press). These tasks and instruction should be designed to clarify language as a symbol system; what writing is; the purpose-specific nature of scientific genre; the author's responsibilities to the audience; the interactive, constructive, generative nature of science language; the relationship between evidence, warrants, and claims; and what, how, when, and why to use specific writing strategies (Hand et al., in press; Keys, 1999). The embedded instruction needs to convert the metacognitive awareness into action to improve self-regulation (planning and generating ideas, translating ideas into text, checking and revising text) and actual writing performance (Hayes & Flower, 1986; Sawyer, Graham, & Harris, 1992). Surveys of teachers and analyses of school writing tasks reveal teachers were unfamiliar with many genres and a dominant use of narrative and factual recounting (Wray & Lewis, 1997). Gallagher, Knapp, and Noble (1993) suggested the need for explicit instruction in a full range of genre (Table 1).

In writing, as in science, form and function are related. Five genres (form-function types) are commonly identified in the writing literature: narrative, description, explanation, instruction, and argumentation. *Narrative* involves the temporal, sequenced discourse found in diaries, journals, learning logs, and conversations. Narratives (document recollections, interpretations, and emotions) are far more personal and informal than most scientific writings. *Description* involves personal, common-sense, and technical descriptions, informational and scientific reports, and definitions. Frequently descriptions will be structured by time-series of events, scientifically established classification systems or taxonomies, or accepted reporting pattern of information (who, what, when, where, why). *Expla-*

Table 1 Genre, purpose, outcome and audience of writing-to-learn science

Genre	Purpose	Outcome	Audience
Narrative	Recording emotions and ideas	Attitudes	Self and others
Description	Documentation of events	Basic knowledge	Others
Explanation	Causality	Cause-effect relationships	Others
Instruction	Directions	Procedural knowledge	Others
Argumentation	Persuasion	Patterns of argument	Others

Adapted from Gallagher, Knapp, & Noble, 1993.

nation involves sequencing events in cause-effect relationships. Explanations attempt to link established ideas or models with observed effects by using logical connectives of "if this, then this." *Instruction* involves ordering a sequence of procedures to specify a manual, experiment, recipe, or direction. Instructions can effectively utilize a series of steps in which the sequence is established by tested science and safety. *Argumentation* involves logical ordering of propositions to persuade someone in an essay, discussion, debate, report, or review. Arguments attempt to establish the boundaries and conditions of the issue and then to systematically discredit, destroy, or support components of the issue, to clearly disconfirm or support the basic premises, or to establish alternative interpretations.

Each genre is flexible, and the writer must control the form to address the function or purpose. No lengthy piece of text uses a single genre (Anthony, Johnson, & Yore, 1996). Analysis of effective writing illustrates microstructures embedded within the macrostructure. In argumentation a writer might start with a descriptive passage to engage the reader, later use an explanatory passage to illustrate a critical cause-effect relationship, and in closing may use an instructional passage much the way a judge clarifies the issues, critical evidence, and the charge to a jury.

Connolly (1989) suggested that this new writing-to-learn rhetoric was compatible with constructivist perspectives of science learning and illustrated that the symbol systems used to communicate play a critical role in constructing meaning. He explained:

> Writing-to-learn is not, most importantly, about 'grammar across the curriculum' nor about 'making spelling count' in the biology paper. It is not a program to reinforce Standard English usage in all classes. Nor is it about . . . mastering the formal conventions of scientific, social scientific, or business writing. It is about the value of writing "to enable the discovery of knowledge." (p. 5)

However, writing-to-learn science tasks do provide authentic opportunities to develop scientific vocabulary, grammar, spelling, punctuation, patterns of argumentation, and technical genre utilized in the science writing and science professions (Koprowski, 1997; Rice, 1998). Writing-to-learn and technical writing have much in common; effective instruction should utilize authentic technical writing tasks to promote science learning, reflection, and practical technical writing.

Howard and Barton (1986) stated that the "idea is to learn to think in writing primarily for your own edification and then the eyes of others. This approach will enable you to use writing to become more intelligent to yourself—to find your meaning—as well as to communicate effectively with others" (p. 14). Holliday (1992) suggested that effective science writers consider their audience and purpose; strategically plan, draft, revise, and edit; and structure writing for maximum effect. Furthermore, they typically read, listen, and speak well and understand language is interpretative, interactive, and constructive.

The following principles should guide the development of writing-to-learn tasks in science (Tchudi & Huerta, 1983):

- Keep science content central in the writing process;
- Help students structure and synthesize their knowledge;
- Provide a real audience for student writers that will value, question, and provide supportive criticism;

- Spend time prewriting, collecting information from various sources (concrete experiences, print materials, experts, electronic data banks, visuals, etc.), sharpening focus, and strategic planning;
- Provide ongoing teacher support, guidance, and explicit instruction;
- Encourage revisions and redrafts based on supportive criticism to address conceptual questions and clarify understandings; and
- Clarify the differences between revising and editing (format, spelling, mechanics, grammar).

These guidelines are clearly illustrated in the science writing efforts currently being used in colleges, universities, secondary schools, and elementary schools.

Colleges and Universities. Hallowell and Holland (1998) stated that "scientific illiteracy among college students is a persistent problem . . . yet the need to understand science principles and to be able to make judgments about the value of scientific knowledge and research has never been greater" (p. 29). Science literacy and the related print-based communication requirements need to address the dual goals (writing-to-learn science and science writing) of the literate adult, the workplace, and the science professional. The University of Hawaii in 1987 adopted a writing-intensive course requirement for AA, BA, and BS degrees in an attempt to enhance students' writing literacy (Chinn, Hussey, Bayer, & Hilgers, 1993). All students must complete five writing-intensive courses in their major area. Writing-intensive courses require that:

1. writing must be used to promote learning;
2. student and professor must interact during the writing process;
3. writing should play a major role in course grades;
4. students must produce a minimum of 4,000 words or 16 pages of text; and
5. class enrollment should be limited to 20 students.

Writing in college/university science to promote epistemic insights, thinking, and conceptual understanding requires utilization of science-appropriate genre (Martin, 1993; Mullins, 1989). Moore (1993) found college students' science achievement improved if writing was coupled with explicit writing instruction and embedded in actual science courses. Liss and Hanson (1993) reported that students who had an internal locus of control appeared to value writing tasks and worked harder than students with an external locus of control. Generally, application of write-to-learn approaches are being more widely used in college/university level science courses than ever before (Ambron, 1987).

The type of feedback provided to university/college writers influences their attitudes and achievement. Iding (1994) found that college composition students benefited most from comments that described the desired changes, such as additional information, local structure, and global structure. Students believed comments that provided a different perspective were useful. Iding and Greene (1995) and Yore (1996) found that peer-review comments were useful to students. The quantity and quality of peer comments could be improved with explicit review and editing instruction (Koprowski, 1997).

Carle and Krest (1998) described a collaborative effort between a science department and university library to improve the access, collection, and evaluation of science information. This program addresses the "out of context" problem that many university library orientation and instruction programs encounter by focusing the effort on science for science majors and instruction on realistic writing tasks for scientists. They utilized print and electronic science citations and references to track the influence of science discoveries and to locate and evaluate information.

Koprowski (1997) and Rice (1998) provided explicit instruction on science writing, exposure to various science writing genres, and actual experience as a reviewer. Koprowski infused writing instruction, writing assignments, and peer-review into an upper-level general ecology course. Students were positive about the overall experience. Rice described an advanced stand-alone scientific writing course designed for upper-level science majors in which he served as "guide, coach, cheerleader, critic and occasionally referee" (p. 268). Central to the success of the course were specific instruction and creatively crafted assignments that provided insights into the different genres scientists use to communicate with different audiences: narrative (scientific autobiography), description, explanation, argument, and report of their original laboratory work (mixed genre). Throughout the course, Rice infused explicit instruction on grammar, appropriate voice, word usage and choice, sentence structure, and logical development at opportune times as needs arose (just-in-time instruction).

Secondary Schools. The major reason for the renewed interest about writing-to-learn science and science writing in secondary schools is the recognition given in major curriculum reform documents, which emphasize students being able to communicate much more broadly than just reporting to the teacher. Students are expected to engage in intellectual public discourse and debate in order to be able to communicate their ideas to others and to maintain or enhance their understanding (Hand et al., in press). Such an emphasis places expectations on the expansion of writing in secondary school science classrooms from the traditional forms of note-taking, laboratory reports, and short-answer tests to incorporate more nontraditional types focusing on encouraging students to inform, explain, defend, debate, and persuade others of their understandings.

Prain and Hand (1996a, 1996b, 1999) provided a framework of five separate but interrelated components to guide improved writing practices within secondary school science classrooms: writing type, writing purpose, audience or readership, topic structure including conceptual clusters, and method of text production including how drafts are produced, both in terms of technologies used as well as variations between individual and collaborative authorship. The framework is intended as both a theoretical model to examine writing-to-learn strategies within science classrooms and as a pragmatic pedagogical model to assist science teachers in the implementation of these strategies.

Harmelink (1998) considered the dual goals of improved science understanding and enhanced science writing effectiveness with the use of journals or learning logs. She recognized science teachers' reluctance based on lack of professional development related to writing and the time limitations of the secondary science curricula, but believed the constructive aspects of writing structured journal entries and related explicit instruction were well worth the time and personal energy invested.

Elementary Schools. Most of the increased interest in writing in elementary school science has to do with the willingness of elementary teachers to expand their language arts program across the curriculum (Baker, 1996). Contemporary approaches in language arts involve establishing a language community in the classroom that addresses a wider variety of authentic speaking, listening, reading, and writing tasks (NCTE/IRA, 1996; Rowell, 1997). There is some hesitation to infuse these language tasks into science, but the recognition that science literacy involves communications to inform others and persuade people to take informed action and the popularity of science-technology-society-environment units have encouraged generalist teachers with strong language arts backgrounds to include writing-to-learn activities in their instructional programs.

Nesbit and Rogers (1997) described how using cooperative learning approaches could improve the print-based language arts in science. The use of culminating writing activities can encourage students to reflect, integrate, elaborate, and consolidate on their science understandings developed during verbal interactions in the cooperative groups (Anthony, Johnson, & Yore, 1996). Peer-review and jigsaw writing activities can be very effective. Wray and Lewis (1997) developed a series of factual writing templates to support young writers in their early attempts to use factual genres. They viewed writing as a social process and the textual product as a social artifact. The use of teacher scaffolding and structured frames allowed students to develop discourse knowledge about the specific genre. Tucknott (1998) explored the effects of writing-to-learn activities infused with an inquiry-based science unit on simple machines, inventions, and inventors. Grade 4 students used several writing tasks—completion of a patent application, summaries of reading materials, laboratory reports, data displays, labeled diagrams, and explanatory paragraphs. The results indicated that teachers needed to use a series of writing tasks that required students to transform their ideas and writing form to increase higher-level thinking and science achievement. The use of transformational tasks appears to achieve revision without repletion. Shelley (1998) described the use of prewriting activities and writing tasks to improve science understanding and to enhance compare-contrast thinking. She notes that "prewriting activities, particularly those including visual aids, focus writing so that students can successfully compare and contrast information" (p. 38). Here again, the structured tasks are sequenced to require students to process and internalize information, not just copy textual materials.

DiBiase (1998) and Linton (1997) utilized inquiry letters to seek relevant information to supplement classroom investigations. Letters designed to request information from experts require students to venture into different language communities. New information technology makes these approaches much more time-efficient and effective.

Recommendations

Based on the collective of literature and experience, the following recommendations were crafted to guide teachers of deaf students in their attempts to infuse science reading and science writing instruction into their teaching. These five recommendations encompass science teaching in elementary schools, secondary schools, colleges, and universities, based on a rich experiential science background, and assume that students are members of a dynamic and adventurous discourse community such as ASL.

1. Ensure any attempts to enhance your students' reading and writing is based on authentic models of reading and writing and valid assessment of the print-based language demands of their science program and their future science careers.
2. Make your reading and writing instruction pay off now and pay off later. Develop authentic science communication tasks that enhance science learning, that enhance adult literacy, and that will enhance professional practice.
3. Make science reading and science writing instruction an integral part of the science program and science courses. Start early and continue throughout the year(s) to elaborate and reinforce effective science communications.
4. Provide embedded reading and writing instruction as a natural part of science learning activities.
5. Explore the use of multi-media to address future demands on science professionals and to maximize motivation.

Promising Practices

The remainder of this article describes three specific instructional practices that reflect the recommendations and address students' science reading comprehension and science writing to enhance their science literacy: habits-of-mind, critical thinking and meaning-making abilities, their understanding of the big ideas of science, and their communications to inform and persuade others in instructional, societal, and professional settings. The process used to select these ideas assessed their power; the appropriateness for the target audience; the background demands on students, teachers, and professors; and the practical utility for science courses of each practice.

Concept Maps

Concept maps—likely one of the most powerful print-based cognitive strategies for elementary, secondary, college, and university students—evolved from schematic webs and stress causality, functionality, application, and hierarchical relationships between concepts and concept clusters. It is believed that concept maps reflect people's conceptual understanding and promote integration of new ideas and old knowledge (Novak, 1990; Wandersee, 1990). The basic building unit of a concept map is a proposition consisting of two concepts linked by a relational word (Figure 4). Propositions can be arranged hierarchically or in clusters of concepts that might be cross-linked to another cluster of concepts.

Concept mapping of difficult science chapters or science units enhances reading comprehension and science understanding (DiGisi & Yore, 1993). A group-

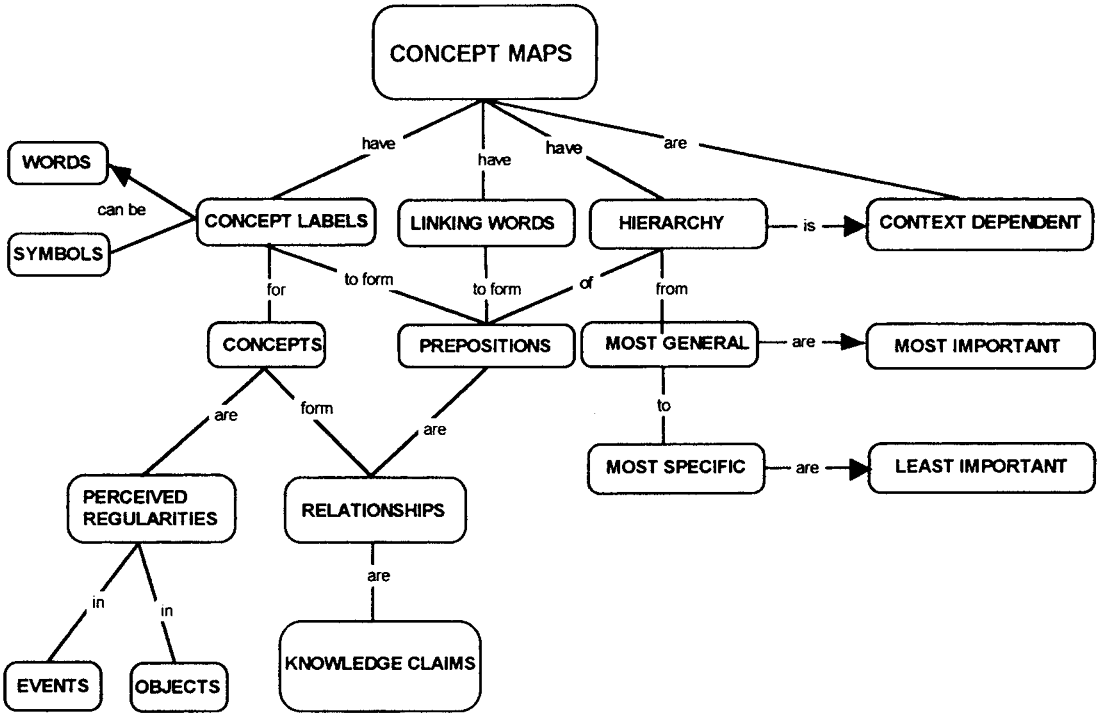

Figure 4 A concept map showing the key concepts involved in concept mapping (adapted from Novak, 1991).

constructed concept map of a complex science topic, after a reading assignment or a series of experiments and lectures as an examination review during a tutorial, is a useful knowledge-building and cognitive synthesis task for students and provides valuable pre-examination assessment information for the students, teachers, and professors or can provide a prewriting activity to initiate a collaborative writing task.

Concept mapping improves students' abilities to identify important ideas and their view of science as a connected body of knowledge (Arnaudin, Mintzes, Dunn, & Schafer, 1984). Using concept mapping requires some class time (1 hour) to construct a demonstration map, to explain the mapping rules, and to allow small-group guided practice in class on a simple, familiar topic: parts of a cell, overview of chemistry, or cosmology (Novak, 1991). This investment pays large dividends, for concept mapping can become a valuable learning tool for students and an alternative evaluation technique.

A group of three or four students can brainstorm the important concepts covered, listing these concepts on 3 × 5 index cards. Collectively, the students negotiate the placement of these cards on chart paper in a hierarchy. They then establish the relations or connections between concepts to form propositions. Propositions are connected to other propositions, forming conceptual clusters. Cross-links between concept clusters can be established to integrate major ideas. Novak and Gowin (1984) provided scoring procedures for assessing concept maps, but a qualitative assessment can frequently identify the conceptual complexity and possible misunderstandings.

Reaction Papers

The reaction paper, a read-write activity, can be used with a variety of students to teach the strategies of summarizing and reflecting and to improve understanding. The example reported here used a series of three reaction papers with undergraduate students taking a required course and involved the students reading a science education, science, or science-technology-society article and writing a one-page summary of and reflection on the article (Yore, 1996). The assignment limited the response space for the article summary to about 125 words and the reaction to about 125 words.

Summarizing is a strategy related to both science reading and science writing, and it incorporates a cluster of subordinate strategies common among science experts. Summarizing requires the writer to recall or comprehend information, to select important main ideas and supportive details, and to craft a concise understandable synthesis of this information while retaining the original author's intent. Hare (1992) described the writer, task, and context variables that influence summarizing (view of task, skill level, prior knowledge, length of information source, genre, complexity, access to information, purpose, length restrictions). She provided specific instructional hints and rules for summarizing—delete redundancies, identify relevant and important ideas, synthesize main ideas into a concise unified text representative of the original author's intentions.

The reflection requires the writer to assess the internal consistency, credibility, and applicational value of the ideas summarized. The writer is expected to deliberate, draw conclusions, and articulate a rationale. Reflection involves many critical response skills, such as evaluating sources; questioning claims, evidence, and warrants; and assessing research methodology (AAAS, 1993). Furthermore, reflection is designed to encourage writers to make connections among ideas found in the summary with ideas from other articles and courses by using cross-references. Quality reflections not only provide a judgment but specify the criteria and thinking used to reach the judgment, thereby reinforcing critical thinking.

Although the audience for these reaction papers was the professor, students were provided complete freedom in the article selected to impress on them the idea that the professor would not necessarily have read the article and therefore had to be considered an interested, but uninformed reader. A copy of the original article was attached to the reaction paper to allow the professor to verify the accuracy of the summary provided. Common language was used to describe the assignment that minimized the necessity for explicit instruction and maximized the free response for the first reaction paper. Explicit instruction following each reaction paper focused on exemplary reaction papers and common concerns. The length restriction was a common early concern, but discussions clarified why it was necessary to limit the response space to necessitate the analysis and evaluation of the article and to avoid the "tell all" approach of novice writers and less critical readers.

Breger (1995) used a similar approach called inquiry papers and a variety of publications to encourage middle school students to learn about science or science-related topics. Bringing together reading and writing into one assignment enhances students' science reading strategies and comprehension of the print material. Writing about what they have read encourages students to organize and react to the ideas that they have just read. The use of periodical literature makes a connection between science and everyday life. The inquiry paper required that students create a reading log in which they wrote down what they predicted they would be reading about, based on the title, the pictures, graphs, and so on. They wrote down key pieces of information that may or may not have agreed with their prediction as they read. These ideas became the "raw material" for the inquiry paper. The summary consists of the main idea with supporting details of "Who? What? Where? When? Why?" Students then reorganize (transform) the summary or key ideas in a visual way, such as a flow chart, concept map, chart, diagrams, showing how the ideas are connected. The third section of the inquiry paper asks the students to choose three words that were important to the concept being discussed in the reading. If any of the words are unfamiliar to the students, the definition should be included in the inquiry paper. The final section of the inquiry paper requires the students to derive three questions that came into their minds during the reading and writing process. At least two of the questions should be science-related. These questions allow students to get involved with the topic, to further understand, or to clarify the ideas presented. The audience for the inquiry paper is the other students, who are encouraged to respond with positive comments, other questions, related readings, or related activities.

Collaborative Explanatory Essay

Explanatory essays need not specify a single genre, but the assignment was expected to promote expository writing that involved analytic strategies of acquiring information and reformulation of personal understandings to inform or persuade an uninformed audience about a specific issue. It was further expected that the task would require an analysis of the audience, an evaluation of the necessity and sufficiency of information, an assessment of the epistemic character and logic of the argument, a clarification of ideas and issues, an explanation of the central position, and an integration of new understandings. Explanatory essays clearly require the writer to explain relationships and apply knowledge (Newell, 1986).

Numerous researchers have encouraged the use of explanatory writing in the content areas to enhance learning (Prain & Hand, 1996b; Rivard, 1994; Schumacher & Nash, 1991). Explanatory essays encourage conceptual change, depth of processing, connecting isolated ideas, and clarification of patterns of evidence, claims, and warrants (Scardamalia & Bereiter, 1986). Kempa (1986) suggested that the following explanatory tasks be used to enhance science learning: (1) developing causal relationships among facts, observations, theories, and models; (2) proposing hypothetical relationships between unfamiliar and familiar ideas; and (3) applying scientific ideas to real-world issues. This type of assignment was used with secondary school students and with undergraduate students (Anthony, Johnson, & Yore, 1996; Yore, 1996). The collaborative explanatory essay was designed to (1) develop insights into the knowledge-transformation model of writing; (2) develop insights about the persuasive, explanatory genre; and (3) develop knowledge about central issues, topic, or idea. The explanatory essay assignment provided a concrete experience with a collaborative, interactive, write-to-learn strategy. The essay assignment used a cooperative learning approach.

In the secondary school setting, a group of at-risk ESL grade 8 students were assigned a descriptive essay on a planet in the solar system. They worked in small, cooperative writing teams to collect information and evaluate ideas but individually wrote the essay. After spending the first class surveying a variety of resources including reference books, encyclopedias, and NASA materials, the students were invited to play "Stump the Visiting Expert." As you might expect, the students asked a series of low-level factual questions. These questions served as the springboard to developing questions requiring a synthesis of ideas and emphasizing higher-level thinking. The higher-level questions framed an information retrieval matrix for the fundamental instructional template to help students set purpose, locate information, and transform ideas. Using the information retrieval matrix (focus questions as column headings and reference materials as row headings), students search for information related to the focus questions. During this process students encounter discrepant information about the planets (length of the year on Mercury as 59 days and as 180 days, on Mars as 87.97 days and as 88 days). This experience clearly illustrated the need to evaluate information, even science information. The teacher modeled the writing task by using information about Earth. The students then used their consensus information on the inner planets to write a descriptive essay using the focus questions. The products were discussed in small groups, and a large group discussion revealed the critical features of an effective descriptive essay.

The explicit instruction carefully modeled each step in constructing an information retrieval matrix and then transforming the matrix into written text about an inner planet required four class periods. Over the next two classes the students applied the process to constructing an information retrieval matrix and writing a descriptive report about one of the outer planets. They worked largely independently of any further teacher direction.

In the university setting, a "jig-saw" approach was used; each member of the "home" group was randomly assigned one of three topics. Students from different "home" groups formed topic-specific "expert" groups. Each expert group collaboratively planned, located information, shared resources, and supported one another; but individual papers were written by each expert. The nonexpert members of the home group (students assigned a different topic) served as an authentic audience for the experts and provided conceptual and editorial feedback on the topical papers for which they were not experts. The peer reviews assessed clarity, conceptual development, appropriateness of examples, and grammar, spelling, punctuation, and writing style. Because students were to be tested on all three topics, they were responsible for developing conceptual understanding by carefully reading these papers and seeking consultation with the expert to clarify any fuzziness. The assignment required a progressive development in which two drafts were submitted for peer review by a different member of their home group. Each draft was revised according to the peer comments and editorial suggestions. The third draft was submitted to the professor for evaluation.

Conclusion

The most difficult issue involved in explicit reading instruction and writing-to-learn activities in science is to convince teachers and professors who did not receive such instruction or experience that such activities are valuable and to be subtle and creative enough not to embarrass or alienate bright, successful students. It is easy to see by a quick review of the references in this article that many science teachers and professors realize that students, even good students, can benefit from explicit science reading and science writing instruction. A trip to a National Science Teachers Association conference, a visit to one's teaching and learning center, or meeting the reference librarian will reveal many things one can do to help students become better communicators.

The more difficult task is not to alienate students, as a referral to the learning assistance class, the skills development center, or the writing clinic might do. In fact, many learning assistance teachers, skills centers staffs, and writing clinics tutors are becoming more proactive, taking a central role in students at risk and new student orientation programs. The most effective way to avoid negative effects is to make explicit reading and writing instruction an integral part of science program and science courses. Three such practices have been described in this article, but numerous others can be used. A group-negotiated "crib card" for examinations stresses the need to critically assess importance. I can recall engraving a 3 × 5 card with so many facts and formulae that I could not read them in the examination. Later I discovered that I could have saved space because Ohms did not create three separate laws dealing with electric current, resistance, and potential. Likewise, critical reading of test items can be enhanced by having students generate prototypical test items/questions that reflect what they think should be tested. Having students generate test questions alerts them to the subtle use of language and provides the teachers and professors with insights on what students think are important. As an introductory writing activity, students can utilize laboratory experiences and a series of templates for writing laboratory reports that stress the epistemic use of evidence, warrants, and claims (Keys, Hand, Prain, & Sommers, 1998). This science writing heuristic extends the use of Vee-diagrams and negotiated understanding. The preliminary results of this writing-to-learn science task reveal improved science achievement and understanding of science as inquiry. Another assignment could explore the appropriate and inappropriate use of graphs, diagrams, and visuals in science materials and the use of communication technologies and software to access information or design a PowerPoint presentation (Hedges & Mania-Farnell, 1998/1999; Maring, Wiseman, & Myers, 1997).

Efforts to enhance students' reading and writing will pay off with increased science literacy, realized academic potential, and effective professional careers. Students will appreciate their teachers' efforts to enhance their print-based communications.

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