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Learning Science Through Writing: The Role of Rhetorical Structures

In a 2 x 2 between-groups study, 85 preservice education students observed a science experiment concerning either buoyancy or the forces acting on a stationary object. Each student then wrote an initial explanation of the phenomenon followed by a journal-style note, then a final explanation. For each science experiment half the students received a list of strategy prompts intended to facilitate learning through writing, and half wrote without these prompts. Forty-three percent of the "buoyancy" students and 14% of the "forces" students increased the complexity of their explanations during the writing interval. Strategy prompting did not increase explanatory gains. Textual analysis showed that for the buoyancy problem, writing comparisons among trials and explanations of individual trials correlated with explanatory gains during the writing interval. For the forces problem, writing a concluding summary correlated negatively with explanatory gains. Qualitative analysis suggested that rhetorical structures (explanation, comparison, argumentation, and summarization) contributed to learning during three phases of building explanations: reviewing experimental trials, analyzing these trials to identify causal variables, and generalizing these analyses to form new explanations. These rhetorical structures stimulated, rather than structured, the construction of new knowledge and mapped onto the logical operations through which writers coordinated hypotheses and experimental trials in a many-to-many, rather than a one-to-one, fashion.

Lors d'une étude intergroupes 2 x 2, 85 stagiaires en pédagogie ont observé une expérience scientifique, soit sur la flottabilité, soit sur les forces agissant sur un objet fixe/stationnaire. Par la suite, chaque étudiant a d'abord écrit une explication sur le phénomène, ensuite une note journalistique et puis une explication finale. Pour chacune des expériences, la moitié des étudiants a reçu une liste d'indices stratégiques visant à faciliter l'apprentissage par la rédaction alors que l'autre moitié n'a rien reçu. Quarante-trois pour-cent des étudiants ayant vu l'expérience sur la flottabilité et quatorze pour-cent de ceux ayant vu l'expérience sur les forces ont augmenté la complexité de leur explication pendant la rédaction. Les indices stratégiques n'ont pas amélioré les explications. Une analyse textuelle a indiqué que, pour le problème sur la flottabilité, une comparaison des textes sur les essais et les explications de chaque essai entraient en corrélation avec les gains en matière d'explication pendant la rédaction. Pour le problème sur les forces, la rédaction d'un résumé de conclusion entre en corrélation négative avec les gains en matière d'explication. Une analyse qualitative semble indiquer que les structures de rhétorique (explication, comparaison, argumentation et résumé) ont contribué à l'apprentissage pendant trois phases explicatives: révision des essais expérimentaux, analyse pour en déceler les variables causales et généralisation de ces analyses pour formuler de nouvelles explications. Ces structures de rhétorique ont stimulé, et non pas structuré, la construction de nouvelles connaissances. Elles se sont également projetées sur les opérations logiques à travers lesquelles les auteurs coordonnaient les hypothèses et les essais expérimentaux d'une façon à correspondance multivoque plutôt que biunivoque.

Authors representing a variety of disciplines have argued that writing is a vehicle for thinking and learning. They have suggested that the gradual pace of

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composing allows writers to reflect on their ideas; that communicating with a remote audience encourages them to make their messages explicit; that the permanence of text allows writers to review their ideas critically and to build on them; and that the need for coherence encourages writers to articulate connections among ideas (Britton, 1982; Emig, 1977; Goody & Watt, 1968; Olson, 1977; Ong, 1982; Vygotsky, 1962; Young & Sullivan, 1984). Consequently, many language teachers in the writing-across-the-curriculum and whole language movements, along with natural science and social studies educators in the constructivist movement, have introduced writing-to-learn activities into their classrooms. A growing body of research has described programs in which writing is used to promote critical thinking and conceptual development (Atwell, 1990; Dillon, O'Brien, Moje, & Stewart, 1994; Fellows, 1994; Guthrie et al., 1996; Johnson, Jones, Thornton, Langrall, & Rous, 1998; Morrow, Pressley, Smith, & Smith, 1997; Prain & Hand, 1996; Roth et al., 1992; Young & Leinhardt, 1998). This literature includes several experimental studies showing that writing contributes significantly to students' recall and understanding of concepts (Beins, 1993; Foos, 1995; Hinkle & Hinkle, 1990; Horton, Fronk, & Walton, 1985; Langer, 1986; McCrindle & Christenson, 1995; Wiley & Voss, 1996).

Writing-to-learn is a constructivist educational practice in the broad sense that it assumes that learning includes relating new experiences to prior knowledge, thinking critically, and generating relationships among ideas (Greene & Ackerman, 1995; Roth et al., 1992; Spivey, 1990). However, in spite of this basic agreement, writing-to-learn remains controversial. Research has left an interrelated set of theoretical and pedagogical problems unresolved. Traditionally, the writing-across-the-curriculum movement has endorsed expressivism. In its purest form, teachers asked students to "free write" journal entries about the personal meaning of educational experiences using language close to speech, or to apply diverse genre associated with the belletristic tradition, such as narrative and poetry, to writing in content areas such as science. When students composed more formal texts, these were often based on expressive foundations (Atwell, 1990; Britton, Burgess, Martin, McLeod, & Rosen, 1975; Calkins, 1994; Fulwiler, 1987; Graves, 1994; McLeod, 1992). However, other educators have challenged the cognitive value of expressive writing (Martin, 1993; Rowell, 1997; Stotsky, 1995). Genre theorists, for example, emphasize writing in traditional academic forms such as scientific reports, expository essays, and analytic essays. They argue that these genre promote depth of processing or elaboration and familiarize students with forms that are socially valued and important for future study and work (Christie, 1985; Langer & Applebee, 1987; Martin, 1993; Newell, 1984; Schumacher & Nash, 1991; Stotsky, 1995; Wiley & Voss, 1996). Yet a third position challenges both of these traditions: Rowell (1997) has claimed that in science education, both expressivism as applied in journal writing and genre theory as applied in the traditional laboratory report convey to students a mistakenly empiricist image of science. Rowell has argued for a multidimensional view of writing in science that includes a hermeneutic dimension in which students appropriate scientific language to support their understanding, a knowledge-transforming dimension in which they reconstruct their knowledge, and a discursive dimension in which they learn conventions that allow them to enter into the discourse of science (compare Sutton, 1996).

A better understanding of how to use writing across the curriculum is particularly important because the success of past efforts has varied widely. On one hand, as noted above, several studies have shown that writing can help students to understand and to recall new concepts. And although advanced writers show greater frequency of complex cognitive operations during writing and higher postwriting levels of understanding, less advanced writers show increases in complex cognitive operations and gains in understanding that are not significantly smaller (Copeland, 1987; Davis, Rooze, & Runnels, 1992; Durst, 1987; Langer & Applebee, 1987). This indicates that composing can benefit students with a wide range of writing skill levels. On the other hand, some studies have found that writing does not affect learning (Tierney, 1985) or that the effects of expressive and elaborative writing do not differ from those of more restricted writing tasks (Greene, 1993; Newell, Suszynski, & Weingart, 1989). And most experimental studies that have shown positive effects on some measures of recall and comprehension have shown no effects on other measures (Audet, Hickman, & Dobrynina, 1996; Boyles, Killian, & Rilieigh, 1994; Hayes, 1987; Hinkle & Hinkle, 1990; Langer & Applebee, 1987; Newell, 1984; Penrose, 1992).

It is particularly important to discover the causes of these inconsistent results because the adoption of writing-to-learn, like any educational practice, makes considerable demands on students and teachers. Traditionally, most teachers have assigned extended writing to evaluate students' knowledge, and most students have accommodated this expectation. Writing for knowledge development rather than knowledge display will require both parties to revise their beliefs and practices (Flower et al., 1990; Langer & Applebee, 1987; Peasley, Rosaen, & Roth, 1992). An additional hurdle is that writing demands time that content area teachers may need to address a prescribed set of topics. Some report feeling unprepared to teach writing, which they believe to be the right and duty of English teachers (Hamilton-Wieler, 1987; Hosic, 1994; Prain & Hand, 1996). And parents may be concerned that courses requiring both content area study and extensive reading and writing will demand too much from their children (Dodd, 1998). Consequently, in order to justify the place of learning-through-writing in classrooms, this practice must be made more consistently helpful to students.

Debates concerning the genre that teachers should assign students beg the more fundamental question, how does writing contribute to learning? For example, vigorous endorsements and condemnations of various genres, discussed above, both assume that the genre that teachers assign shapes the concepts that students will learn. It is often expected, for example, that assigning analytic essays will cause students to think critically or that asking students to write an analogy will cause them to apply knowledge from one situation to a new situation. However, the effects of genre on learning are highly variable; the form that teachers assign is often not the form that students adopt; and the form that students adopt does not consistently determine the conceptual relationships that they learn (Greene, 1993; Penrose, 1992). More generally, studies of the cognitive processes through which writing affects learning have been rare, although theories have been numerous (for reviews, see Ackerman, 1993; Klein, in press; Schumacher & Nash, 1991).

Theoretical proposals concerning writing-to-learn can be discussed in relation to three phases of composing: planning, production, and revision. The goal-directed procedures that writers employ during these three phases are referred to here as strategies. Writers may employ *planning* strategies before composing the first draft of a text. These can include setting rhetorical goals, then defining content problems on the basis of these goals, and working to solve these problems (Bereiter & Scardamalia, 1987). They can also include choosing to incorporate rhetorical structures such as argument, explanation, comparison, or summary. *Production* strategies involve generating either ideas or language and transcribing these. They can include reflecting on experiences to generate ideas, writing whatever comes to mind, or searching for more ideas about which to write (Britton, 1982). Revision strategies occur after the initial drafting of the text. They can include rereading the draft to generate new inferences (Young & Sullivan, 1984); revising text to incorporate ideas that have emerged during writing (Flower & Hayes, 1980, 1981a); or evaluating whether the text represents "what I really mean" (Flower & Hayes, 1981b). Writers often intersperse these strategies rather than employing them sequentially (Flower & Hayes, 1980, 1981a).

This study attempted to address three questions: First, does prompting students to adopt these planning, production, and revision strategies facilitate the construction of new explanations? (see Appendix A). Second, does composing text that includes genre-related rhetorical structures such as argumentation, comparison, explanation, or summary contribute to explanatory gains? And third, how (i.e., through what processes) do these rhetorical structures contribute or fail to contribute to students' transformation of specific content during writing?

This research addressed these questions in the context of two science experiments. Experimentation followed by journal writing has become a popular, although not dominant, practice at all levels of science teaching (Atwell, 1990; Audet, Hickman, & Dobrynina, 1996; Malachowski, 1988). However, experimental studies of writing-to-learn have most often focused on reading-to-write tasks in the social sciences or humanities (Ackerman, 1993), leaving the role of writing in science a relatively unexplored area. Science educators have noted this gap and expressed considerable interest in how writing might shape learning in their discipline (Glynn & Muth, 1994; Rivard, 1994).

The first science problem in the present study concerned buoyancy. Inhelder and Piaget (1958) described a series of increasingly sophisticated conceptions that emerged from preschool through adolescence: Very young children often offered contradictory explanations of buoyancy, for example, claiming that one object floats because it is light, and another sinks because it is light. From 7 to 9 years they typically recognized that each material has a characteristic weight that affects its buoyancy, a conception the researchers called specific gravity. At 9-10 years, children's explanations began to refer to the effect of volume on buoyancy. At 11-12 years of age they discussed the relationship between weight and volume, recognizing that an object sinks if it is "heavy for its size." Finally, young adolescents sometimes referred to the weight of an object relative to an equal volume of water. Subsequent studies have shown that although students show some awareness of density as early as 4 to 5 years of age, some retain alternative conceptions through secondary school and university (Ginns & Watters, 1995; Kohn, 1993; Smith, Carey, & Wiser, 1985; Stepans, Beiswenger, & Dysche, 1986).

The second science problem concerned the forces acting on a stationary object. When a book, for example, rests on a table, two forces act on it: The force of gravity attracts the book to the earth; and the table exerts an equal force upward. Many students appear to equate force with movement, so they do not recognize the reaction force exerted by the table, a conception that sometimes persists following instruction (Clement, Brown, & Zeitsman, 1989; Finegold & Gorsky, 1991; Minstrell, 1982). However, most students do recognize that a flexible object such as a spring exerts a reaction force when compressed. This has formed the basis for instructional strategies based on analogy. For example, students can initially be presented with a book resting on a spring in order to provide an "anchoring intuition" representing the reaction force. They then are presented with bridging situations such as a book resting on a flexible board. This assists students in then recognizing by analogy that the stationary, seemingly rigid table also exerts a reaction force upward on the book (Brown & Clement, 1989; Clement et al., 1989; Minstrell, 1982).

In the present study education students observed one of two science demonstrations: buoyancy or forces acting on a stationary object. They recorded their initial explanation of the demonstration that they observed, then wrote an informal journal-style note about it. Half of the students received a list of 15 writing strategy prompts, and half wrote without such prompts. Students then recorded their final explanation of the demonstration. The dependent variable of interest was whether or not students' explanations improved during the writing interval.

Method

Participants

The participants were preservice education students, preparing to teach children at the junior and intermediate levels (grades 4-10). Their program included a general introduction to each area of the elementary school curriculum, as well as specialization in one subject area. Science is the subject that elementary educators most often report feeling inadequately prepared to teach. Nevertheless, most of these highly literate candidates had successfully competed for admission to an education program based on their high undergraduate achievement in humanities, social sciences, or fine arts programs, suggesting that they might particularly benefit from using writing as a vehicle for learning science.

Four classes including a total of 104 students participated in the activities described here as part of a required science workshop series. Students made an informed, anonymous decision as to whether their writing would be used as data for this research, bringing the actual sample size to 85. Of these, 72% of the students were female, 26% were male, and 2% chose not to indicate gender. Their mean age was 26.3 years (*SD*=5.8). All held a previous Bachelor's degree, and one student held an additional Master of Arts degree. Their undergraduate majors included the humanities (41%); fine arts or physical education (16%); science, mathematics, or technology-related disciplines (25%); and social sciences (19%). Thirty-two percent of the students had not completed any previous university science courses, but this distribution was positively skewed, ranging up to 16 full courses (M=3.73, SD=6.58).

Procedures and Materials

Previously, at registration, students preparing to specialize in each curriculum subject had been assigned arbitrarily to classes, although no formal randomization procedure was used, so that each of the four classes that participated in this study included students from each subject area. A Kruskal-Wallis one-way analysis of variance showed that the number of science courses that students had completed during their Bachelor's degrees did not differ significantly among classes, $X^2(3)=1.95, p>.05$. Two of the classes were randomly assigned to the buoyancy problem and two to the forces problem. For each science problem one class was randomly assigned to the prompted condition and one to the unprompted condition. This produced four groups: buoyancy-prompted writing; buoyancy-unprompted writing; forces-prompted writing; and forces-unprompted writing.

Buoyancy Experiment

Materials included a large, transparent tank of water; a mat with three sections, labeled "Float," "Sink," and "Other"; and a set of objects including: (a) a small wooden block (10 cc, 6 g); (b) a large stone (70 cc, 187g); (c) a small stone (11 cc, 27 g); (d) a large wooden block (845 cc, 435g); (e) a sealed plastic vial filled with salt (180 cc, 216g); (f) a sealed plastic vial filled with wheatgerm (180 cc, 57 g); (g) a sealed plastic vial filled with water (180 cc, 178 g); (h) a medium-sized wooden block (88 cc, labeled "50 g"); (i) a smaller wooden block equal in weight to (h) (42 cc, labeled "50 g"); and (j) an aluminum can with a hole in the bottom (200 cc, 32g empty, 230 g when filled with water). The materials also included a booklet with questions. The initial question was "What makes objects float or sink?" with a ruled space where students could record their answers. This was followed by "Please write a brief note about the experiment. What, if anything, did you learn? How did you learn this?" with a ruled space for a one-page, journal-style note. The final question was, "What makes objects sink or float? Is your explanation the same, or different, from the one that you gave before writing your note?" In addition, students in the prompted group also received lists of strategy prompts immediately before writing designed to facilitate learning-through-writing (see Appendix A).

First, students in both the prompted and unprompted groups observed the buoyancy experiment. Objects were tested one after another in the water tank, then moved to the appropriate section of a mat marked "Float," "Sink," and "Other."

After the demonstration, students in both the prompted and unprompted groups recorded their initial explanations concerning buoyancy by writing an answer to the question "What makes objects float or sink?"

Next, the researcher said, "Please write a brief note about the experiment. What, if anything, did you learn? How did you learn this? Some people have described using writing as a way of learning. Please write a note about the experiment that you just observed. As you are writing, try to build a better explanation of what makes objects float or sink." Students in the prompted group received the page labeled "Suggestions for Writing" (see Appendix A). The researcher said, "Here are some suggestions for writing. Please read them over before writing. If you use any of the suggestions, please check them off in the space at the left." Students in both the prompted and unprompted groups completed the writing task in approximately 15 minutes.

After writing their notes, students were asked to record a final explanation by answering the same question again, "What makes objects sink or float?" They were also asked, "Is your explanation the same or different from the one that you gave before writing your note?"

Forces Problem

Materials included: (a) a large book resting on a large, loosely-wound spring that compressed visibly; (b) a similar book resting on a thin board that flexed visibly; (c) a similar book resting on a wooden table. Writing materials were identical to those for students in the buoyancy problem, but the initial and final questions were, "A book is resting on a table. What forces are acting on it? Please add a small sketch." The sheet of writing strategy prompts was identical to that used for the buoyancy problem (see Appendix A).

Procedurally, the objects for the forces demonstration had been set in place as a stationary exhibit before class. The researcher directed the class's attention to the demonstration, then gave instructions for the writing task that were identical to those given for the buoyancy problem except for the change in the initial and final questions stated above.

In summary, for both science experiments, students (a) observed the demonstration; (b) wrote their initial explanation; (c) wrote a journal-style note about the demonstration with or without access to a list of strategy prompts; and (d) and wrote their final explanation. The total time was approximately 35 minutes.

Analysis

Analysis took place in four steps. First, the students' initial and final explanations of buoyancy were classified according to five categories (see Table 1). These categories were considered ordinal levels because their ranking corresponds to the results of previous developmental and instructional research; these categories were not considered interval levels because there was no reason to assume that the differences between consecutive categories were equal (Ginns & Watters, 1995; Inhelder & Piaget, 1958; Kohn, 1993; Stepans et al., 1986). Based on this, students whose final explanations were at a higher level than their initial explanations were classified as showing "gains" during the writing interval. For example, if a student initially explained buoyancy on the basis of weight alone and finally explained buoyancy on the basis of "weight for its [an object's] size," then the student's text was classified as showing an explanatory gain. Students' written answers to the question "Is your explanation the same, or different, from the one that you gave before writing?" agreed with the judgment of the researcher in 89% of all cases. Similarly, students' initial and final explanations of forces were scored according to three ordinal categories based on previous research (Clement et al., 1989;

Table 1
Students' Initial and Final Explanations of Buoyancy

Explanation	*Example*	*Initial (n=42)*	*Final (n=42)*
Weight	"it depends how much they weigh. Light things float."	21%	10%
Substance	"things with air in them float."	14%	14%
Qualitative density	"objects sink if they are made of a heavy kind of material."	50%	48%
Density a function of weight/volume	"how heavy it is for its size."	2%	5%
Density relative to medium	"it sinks if it is heavier than an equal volume of water."	12%	24%

Finegold & Gorsky, 1991; Minstrell, 1982; see Table 2). Students' written answers to the question "Is your explanation the same, or different, from the one that you gave before writing?" agreed with the judgment of the researcher in 100% of cases.

In the second phase of the analysis, the effects of the science problem (buoyancy versus forces) and procedural facilitation (prompted versus unprompted) on the dependent variable of explanatory gains, were tested using the Mann-Whitney U-Wilcoxon Rank Sum W test. This nonparametric analysis was selected because the dependent variable was ordinal.

Third, given that individual students chose different strategies in the course of writing, the question was asked, which of these were associated with learning during the writing interval? Analysis focused on four strategies that left traces in the text in the form of rhetorical structures: comparing trials, explaining each trial, arguing for an explanation, and concluding with a summary. Each student's text was analyzed by both the researcher and a second, independent rater and categorized as including or not including at least one instance of each of these four rhetorical structures. Agreement between raters was 79%, an acceptable level. Subsequently, disagreements were resolved by discussion. A nonparametric Mann-Whitney U-Wilcoxon Rank Sum W test

Table 2
Students' Initial and Final Explanations of Forces Acting on a Stationary Object

Explanation	*Example*	*Initial (n=43)*	*Final (n=43)*
Gravity only	"gravity weighs down the book."	49%	33%
Gravity, opposing entity noted, but not as a force	"The table holds the book at that point ... it's not a force."	14%	19%
Gravity and reaction force	"Gravity pushes down ... table pushes back up to balance it."	37%	49%

was used to determine whether each of the four rhetorical structures discriminated between students who made explanatory gains and those who did not.

The fourth part of the analysis addressed the question, in what ways do these four rhetorical structures contribute, or fail to contribute, to learning during specific writing episodes? A qualitative analysis was carried out on the texts of all 85 students. The texts were read closely with attention to each students' initial explanation, the rhetorical structures that appeared in the text (explanation, comparison, argumentation, summarization), the specific trials to which these rhetorical structures referred, and any changes in the student's explanations.

Results

General Analysis

Overall, 24 of the 85 students, or 28%, made explanatory gains, and one regressed during the writing interval, Wilcoxon Matched-Pairs Signed-Ranks test, $Z=-4.03$, $p<.01$. Of the forces students, 37% wrote initial explanations that referred to both gravity and the reaction force, which were ranked at the highest level; of the buoyancy students, 12% wrote initial explanations that referred to the density of the object relative to water, which were ranked at the highest level. Consequently, significantly more forces students initially scored "at ceiling," Mann-Whitney test, $Z=2.69$, $p<.01$. Among the other 64 students whose initial explanations were not at ceiling, a significantly greater proportion of buoyancy students (49%) than forces students (22%) made gains during the writing interval, Mann-Whitney test, $Z=-2.14$, $p<.05$. Prompting writing strategies did not significantly affect explanatory gains: 26% of the prompted students improved their explanations during writing, and 30% of the unprompted students did so, Mann-Whitney test, $Z=-.41$, $p>.05$.

Buoyancy Problem

Experimental results. In the buoyancy problem, the most frequent explanation, both before and after writing, was qualitative density, for example, that some kinds of materials are "heavier" or "more solid" than others (see Table 1). Initial explanations did not differ significantly between the prompted and unprompted groups, Mann-Whitney test, $Z=-1.25$, $p>.05$, confirming the similarity of the groups before writing. Following writing the qualitative density conception of buoyancy remained most popular, but the conception that the density of an object relative to water determines its buoyancy increased substantially in frequency; 43% of students made explanatory gains during the writing interval, Wilcoxon matched-pairs signed-ranks test, $Z=-3.22$, $p<.01$. This included 48% of the prompted students and 37% of the unprompted students; a Mann-Whitney test showed that this difference was not statistically significant, $Z=.71$, $p>.05$.

Internal analysis. Recall that in order to explain why some students made gains during writing whereas others did not, each text was examined for the presence of four rhetorical structures: explanation, comparison, argumentation, and concluding summary. As Table 3 shows, somewhat more than half the students included comparisons and explanations of each of the trials, and a substantial minority included arguments or concluding summaries. In total,

Table 3
Percentage of Students Using Four Rhetorical Structures,
By Science Task and Instructional Group

Structure	*Buoyancy*			*Forces*		
	Unprompted (n=23)	*Prompted (n=19)*	*Z*	*Unprompted (n=20)*	*Prompted (n=23)*	*Z*
Comparison	70%	84%	−1.10	50%	65%	−1.00
Explanation	39%	63%	−1.53	65%	83%	−1.30
Argument	39%	42%	−.19	50%	57%	−.42
Concluding summary	35%	42%	−.48	25%	43%	−1.25

*p<.05 (1-tailed)

69% of the students used two or more different kinds of rhetorical structures, and 43% used three or more different kinds. Although the prompted group used all four structures slightly more frequently than the unprompted group, these differences were not significant (see Table 3).

Table 4 summarizes the use of these structures by students whose initial explanations did not receive maximum ratings. These students were selected for this analysis because unlike the students who initially scored at ceiling, they had space to make explanatory gains or not. The first row shows that 59% of students who wrote comparisons made explanatory gains, whereas only 20% of those who did not write comparisons made such gains, Mann-Whitney test, $Z=-2.09, p<.05$. Similarly, students were significantly more likely to make gains if they wrote explanations of individual trials than if they did not, $Z=-1.78$, $p<.05$. Of students who wrote arguments, 63% made explanatory gains, and of those who did not 38% made gains, but this difference fell slightly below statistical significance, $Z=-1.45, p=.056$. In addition, for writers who used one or more different kinds of rhetorical structure, the number of structures used correlated positively with explanatory gains, τ-b (32)=.33, $p<.05$.

To summarize these results, prompting did not affect explanatory gains, nor did it affect the frequency with which students used four rhetorical structures in their texts; however, more of the students who wrote comparisons, explanations, and possibly arguments made explanatory gains during writing.

Qualitative analysis. Recall that to illuminate further how these writing structures (comparison, explanation, argumentation, summarization) may have mediated or failed to mediate the transformation of students' knowledge, a qualitative analysis was carried out on the texts of all 42 students who participated in the buoyancy problem. Specifically, the questions asked concerning each student's text were, "Was the student's initial explanation at ceiling or not? Did the student discuss trials critical to this initial explanation, that is, trials for which this explanation did not account? Did the student infer the influence of a new variable in writing about these critical trials? And did the student generalize this new variable by including it in the final explanation, that is, did the student make explanatory gains?" Table 5 shows a general

Table 4
Percentage of Students who Made Explanatory Gains,
As a Function of Inclusion vs. Noninclusion of Four Rhetorical Structures

Structure	*Buoyancy Task (n=37)* *Included Structure?* *Yes*	*No*	*Z*	*Forces Task (n=27)* *Included Structure?* *Yes*	*No*	*Z*
Comparison	59%	20%	−2.09*	25%	18%	−.41
Explanation	65%	35%	−1.78*	21%	25%	−.22
Argument	63%	38%	−1.45	9%	31%	−1.34
Concluding summary	39%	54%	−.90	0%	33%	−1.93*

*p<.05 (1-tailed)

pattern in which many students included elements of any given rhetorical structure, but attrition occurred at every stage of applying these structures. For example, in the first row the second column shows that 21 buoyancy students wrote explanations of each experimental trial; 4 of these students' initial explanations referred to the density of objects relative to water, so they received the maximum score and were not considered eligible to make further gains; the other 17 students offered simpler initial explanations and so had space to improve on these. Continuing across the column, of these 17 students, 15 selected trials that bore critically on their explanations, that is, trials that were not validly covered by them; the other 2 students discussed only trials consistent with their initial explanations. Of these 15 students, 12 inferred the influence of a new variable based on these critical trials, whereas the other 3 did not. Of these 12 students, 11 generalized the new variable in their final explanation, whereas the other treated the new variable as relevant only to the critical trials. In summary, of the 17 students who included explanations in their texts, 11 addressed critical trials, analyzed these to identify new variables, and retained these new variables in their final explanations. I now discuss examples of how students used these rhetorical structures to transform, or not to transform, their explanations.

Comparison. In the buoyancy problem most students wrote comparisons that referred to critical trials, identified new independent variables, and generalized these variables in their final explanations. For example:

> [Initial explanation]: Their [the objects'] weight, consistency, shape.
>
> [Text excerpt]: But on the other hand, a large shaped [sic] 50 gram block floated whereas a smaller 50 gram block sank, which could be attributed to the size or shape of the blocks.
>
> [Final explanation]: If something is heavy for its size it sinks and if something is light for its size, it floats.

Conversely, writing comparisons failed to support explanatory gains if students discussed only the trials that differed with respect to variables that they had already identified in their initial explanations or when they selected

Table 5
Type of Rhetorical Structure, Level of Initial Explanation, and Application to Experimental Trials

Rhetorical structure		*Initial Explanation*		*Application of Rhetorical Structure*		
		Ceiling	*Nonceiling*	*Selected Critical Trials*	*Analyzed Trials*	*Generalized Variable*
Explanation						
Buoyancy	*n*=21	4	17	15	12	11
Forces	*n*=32	13	19	19	14	4
Comparison						
Buoyancy	*n*=32	5	27	21	17	16
Forces	*n*=25	9	16	14	5	4
Argument						
Buoyancy	*n*=17	1	16	11	10	10
Forces	*n*=23	12	11	10	5	1
Concluding Summary						
Buoyancy	*n*=16	3	13	7	5	5
Forces	*n*=14	6	8	8	5	0

critical trials but for unknown reasons did not abstract any new variables (see Table 5).

Explanation. In writing about the buoyancy problem most students discussed the various trials in the order in which they were demonstrated. To the first few trials they applied their relatively incomplete initial explanations. Then, when they reached trials that bore critically on these, they generated more complex explanations. In effect, explaining each trial extended their reviews of the experimental results and circumvented the need for them to select critical trials intentionally. After generating complex explanations based on these critical trials, most participants retained these in their final explanations (see Table 5).

Argument. In the buoyancy problem several students repeated their initial explanations as claims at the beginning of their journal notes. Then, in the course of presenting experimental trials to provide evidence for these claims, they recognized that different explanations actually followed from the data. For example:

> [Initial explanation]: I would think that the weight of an object would determine whether it would float or sink.
>
> [Text excerpts]: The objects which were heavier did indeed sink ... However there were a few objects that did not fit my theory. For example, both the larger and smaller rock sank. The majority of blocks floated, except for the smaller 50 g block, that one sank, compared to the larger block. I think it is not so much the size, but more the mass and the material of the object. For example, you could have a large plastic ball, and a small rock. The large object you would think would sink, but it is plastic, which is a light material, so it can keep afloat. [Note:

> This participant seems to use "mass" to mean the characteristic weight of a "material."]
>
> [Postwriting explanation]: the material which the product is made of.

However, argumentation appeared to contribute to explanatory gains in other ways as well. Three writers tentatively proposed new explanations in their notes, then used the experimental results to argue for these. Two writers initially proposed more than one explanation, then eliminated one of these by identifying counterexamples to it and retained the more complex explanation as the final one.

Concluding summary. Recall that in the buoyancy problem this rhetorical structure did not differentiate significantly between students who made explanatory gains and those who did not. Only about half the students whose initial explanations were not at ceiling and who wrote a concluding summary discussed critical trials in their texts (see Table 5). This suggests that many students who wrote a concluding summary did so prematurely before examining an adequate range of experimental trials. Of the students who wrote concluding summaries, only those who also used at least one of the other three kinds of rhetorical structures made explanatory gains.

Of the five students who included a concluding summary and made explanatory gains, two wrote their new explanations before the concluding summary, so it did not appear to contribute to inferring the effects of the new variable. The remaining three students each used the concluding summary differently from one another. One student had discussed the separate effects of weight and volume earlier in her text. In the final sentence she integrated these two factors using the concept of density. The second student had explained buoyancy in terms of density alone throughout the text. In the summary sentence she wrote, "This [density] was the main discovery of the experiment but also the jar filled with water added to the discovery since the water would have to have the same density as the water in the jar." In this way she extended the explanation to cover a case that she had not yet discussed. She retained this extended conception in her final explanation. The third student critically discussed evidence for the effects of weight, size, and material in the body of her note, then in the summary sentence she highlighted the critical variable and dropped the other explanations: "I think that density is still the most plausible interpretation ... now I feel more confident about it. Density is the key to buoyancy."

Forces Problem

Experimental results. Students' most frequent initial explanation referred only to gravity and did not mention the reaction force from the table (see Table 2). Consistent with the previous random assignment of students to classes, initial explanations did not differ significantly between the prompted and unprompted groups, Mann-Whitney U-Wilcoxon Rank Sum W Test, $Z=-1.10$, $p.>05$ (see Table 3). Fourteen percent of the students' explanations improved during writing, so that the most frequent final explanation included both gravity and the reaction force from the table. A Wilcoxon Matched-Pairs Signed-Ranks test showed that this represented a significant improvement, $Z=-2.46, p<.01$. Ten percent of the prompted students' explanations improved, and 17% of the unprompted students' explanations did so, an insignificant difference, Mann Whitney test, $Z=-.69, p>.05$.

Internal analysis. The rhetorical structures of comparing trials, explaining each trial, and arguing for an explanation were each used by more than half the forces students. Seventy-two percent of the students used two or more different kinds of structures, and 42% used three or more kinds. As Table 3 shows, all four of the structures were used somewhat more frequently by the prompted group than the unprompted group, but these differences were not significant.

Table 4 represents the 27 students who did not score at ceiling on their initial explanations, and therefore had the opportunity to make explanatory gains. The presence of most rhetorical structures did not discriminate significantly between students who made gains during writing and those who did not. However, of students who wrote concluding summaries, 0% made explanatory gains, whereas of those who did not, 33% made gains, a significantly negative relationship, $Z=-1.93$, $p<.05$. For students who used one or more kinds of rhetorical structures, the number of structures used correlated negatively, but not significantly, with explanatory gains, $\tau\text{-}b\ (23)=.28, p.>05$.

Qualitative analysis. Table 5 shows that most students applied rhetorical structures to trials that bore critically on their initial explanations. Of these, some identified a new explanatory variable, that is, the reaction force. And of those who identified the reaction force, some generalized this variable to their final explanation concerning the book on the table. However, in the forces problem, unlike the buoyancy problem, most students who attempted to apply these rhetorical structures did not construct final explanations more complex than their initial ones. Instead, most of the students who used these structures to write valid statements had already scored at ceiling by identifying both gravity and the reaction force in their initial explanations.

Comparison. Recall that in the forces problem, comparisons in students' notes did not differentiate between those who made explanatory gains and those who did not (see Table 4). As Table 5 indicates, most students who attempted to write comparisons referred to the critical trial in which a book was placed on a spring. However, most did not infer that the force exerted by the spring was a common factor shared by all three trials. Instead, they saw the reaction force as a point of difference among them:

> [Initial explanation]: Gravity is acting on the book.
>
> [Text excerpts]: The force of gravity is acting differently upon each book seeing as they are presented differently on the table (one flat on the table, one on a board above the table, and one on a spring) ... If I were to touch the spring, there would be another force acting on the book which would make the spring bounce back up away from the table. There wouldn't be any movement like this with either of the other 2 books.
>
> [Final explanation]: Gravity—no change from before.

However, writing comparisons appeared to allow a few students to abstract the reaction force as a common factor among the spring trial and other two trials:

> [Initial explanation]: Gravitation.

> [Text excerpts]: Three books: One resting on the flat surface of the table; one elevated by two blocks of wood resting on a piece of wood and the third balanced on a coil ... I learned that gravitation is one of the forces acting on all three books, no matter where its placement is ... the force of the coil, as well as the wood under the other two books counters the force of gravity.
>
> [Final explanation]: Gravity and the other force that *counters* the force of gravity.

Explanation. Most forces students who wrote explanations of each trial did not make explanatory gains. A few did not identify the reaction force in any trial; most correctly identified the reaction force in the spring trial, but did not generalize this insight to the other two trials (see Table 5). Most students who made gains applied their initial, incomplete explanation to at least one of the trials, then identified the reaction force in the spring trial. Subsequently, in their final explanation they generalized this reaction force to all three trials:

> [Initial explanation]: Gravity is acting on it [the book] now.
>
> [Text excerpts]: The first trial has the book resting on the table ... When the book is placed on the wood, the wood bent slightly, from the force of gravity pulling on the book ... When the book is placed on top of the spring, the spring moved down, reacting to the force of the book.
>
> [Final explanation]: What I learned is that there is a force pushing back on the book at all times, only the piece of wood and the spring allowed me to see this force in action.

Argumentation. As with the explanation structure and the comparison structure, most forces students who wrote arguments either did not identify the reaction force in any of the three trials or ascribed it only to the spring (see Table 5). Only one student who used argumentation made gains. He initially listed one explanation, then in the course of discussing evidence for it he generated a different one.

> [Initial explanation]: The force of gravity is working on the book as it is laying on the table.
>
> [Text excerpt]: In each of the above trials, the force acting on the book was the force of gravity ... In trials 2 and 3 there was also another force, that exerted by the board and the spring respectively. If the book in trial 2 was pushed down on either side of the center, it would fall and in trial 1 it would remain stationary, however in trial three the spring would push the book back up to where it began. [He scratched out the second of these sentences and wrote]: In all three trials, there was also another force, that exerted by the table, the board, and the spring.
>
> [Final explanation]: The forces acting are the force of gravity, and the other force. This is a different explanation.

Concluding summary. Recall that in the forces problem writing a concluding summary correlated negatively with explanatory gains. Most students who included summaries discussed critical trials in the body of their texts, but as with the other three rhetorical structures (comparison, explanation, argumentation) some writers did not identify the reaction force in any trial, whereas others identified it only in the spring and did not generalize this inference to the book, so the concluding summary repeated the initial explanation.

> [Initial explanation]: Gravity.
>
> [Text excerpts]: I learned that gravity works even if a book is balanced in different ways (i.e., on a block of wood) ... That gravity seems to work in many different ways (works on a flat table and also with objects holding or balancing in the air) ... In conclusion, I have learned that gravity works in many different situations and is stronger than other forces, exemplified in the balancing by the wood and the spring.
>
> [Final explanation]: Gravity.

Discussion

This study sheds light on both the effectiveness and the fragility of learning-through-writing. For both science problems a significant proportion of students constructed explanations during the writing interval that were more complex than those that they held initially. In the buoyancy problem most students who wrote explanations, comparisons, and arguments made explanatory gains. But in the forces problem, comparisons, explanations, and arguments did not correlate with explanatory gains, and writing concluding summaries correlated negatively with such gains. Prompting students to use specific strategies had no significant effects. This may be because, judging by the frequency with which students in the unprompted group used four strategies that left structural traces in their texts (comparing, explaining, arguing, and summarizing), most students spontaneously wrote elaboratively, regardless of whether they were instructed to do so.

The qualitative analysis indicated that writing supported learning in these science problems during three overlapping, sequential phases. First, writing extended the *search* for a solution to the science problem. This was evident when composing explanations or arguments led students to review many or all of the experimental trials, eventually addressing those that bore critically on their initial explanations. Second, writing allowed students to *analyze* these experimental trials. For example, when writing explanations, students articulated the effects of variables that were salient in specific trials; when comparing, they noticed factors that correlated with differences in buoyancy. Third, these rhetorical structures allowed students to *generalize* their newly generated analyses; they did so, for example, by applying a new explanation to subsequent trials or by extending the role of an explanatory variable in a concluding summary. Although overall in the forces problem none of the four rhetorical structures correlated positively with explanatory gains, the qualitative analysis suggested that some students used comparison, explanation, or argumentation to generate new explanations successfully.

The relationship between rhetorical structure and learning was consistent with some aspects of both expressivism and genre theory and inconsistent with others. On one hand, as expressivists would expect, many students were able to construct new knowledge while writing an informal, personal, journal-style note in response to the questions "What did you learn? How did you learn this?" And, as genre theorists would predict, students appeared to construct this knowledge using rhetorical elements of analytic texts: comparison, explanation, and argumentation.

On the other hand, as noted in the introduction, both expressivists and genre theorists have usually assumed that the structure of the texts that students compose shapes the knowledge that they create. In contrast, previous research has shown that the genres that teachers assign and students adopt are only weakly related to what students learn during writing (Greene, 1993; Hayes, 1987; Penrose, 1992; see Klein, in press, for a review). The present study helps to explain this discrepancy between text genre and knowledge structure. The application of rhetorical structures appeared to prompt new inferences rather than to structure such inferences directly. For example, when students wrote comparisons between the large 50-gram block that floated and the small 50-gram block that sank, this comparison did not constitute the explanation that "weight for size" affects buoyancy, but it prompted several students to generate this new inference. Similarly, writing arguments led students to search for evidence by examining critical experimental trials; these formed the basis for new explanations, although these new explanations were not themselves instances of argumentation.

More generally, the effects of writing on learning appeared to be heterogeneous on three levels. First, the effectiveness of writing differed significantly between two science problems. Second, the types of rhetorical structures that correlated with gains in the buoyancy problem did not correlate with gains in the forces problem. Third, for each science problem a given rhetorical structure could evoke diverse logical operations. For example, in the buoyancy problem argumentation variously led students to disconfirm an initial invalid explanation, to affirm a tentative valid explanation, or to subsume a simple explanation under a more complex one. In summary, these four rhetorical structures (explanation, comparison, argumentation, summarization) mapped onto the logical operations through which writers coordinated hypotheses and experimental trials in a many-to-many rather than a one-to-one fashion.

However, although the effects of writing on learning were partly unpredictable, they were nevertheless interpretable retrospectively. The qualitative analysis showed that for most students their final explanations could be accounted for by referring to their initial explanations, the rhetorical structures that appeared in their texts, and the experimental trials to which they applied these structures. For example, in the buoyancy problem, writing comparisons operated most often by allowing students to correlate differences between objects in characteristics such as density, with corresponding differences in buoyancy; in the forces problem, comparisons operated by allowing students who had identified the reaction force in the spring trial to generalize this to the table trial.

These findings raise a critical question: Is writing-to-learn psychologically real, that is, is it a process that is coherent and distinct from other learning activities? Previous research has shown that in nonwriting contexts many participants solve physics problems using the same case-based or analogical reasoning that students used in this study (Brown & Clement, 1989; Clement et al., 1989; Hardiman, Pollatsek, & Well, 1986). Moreover, the rhetorical structures that students used in the present study are not unique to writing; for example, self-explanations characterize the verbal protocols of students who learn from textbooks to solve physics problems (Chi & Bassok, 1988). Therefore, further research is needed to examine the extent to which writing itself affects learning. Young and Sullivan (1984) have proposed that writing is necessary for some kinds of thinking and discourse because it preserves ideas in text, allowing writers to review these ideas and generate new relationships among them. They have provided some anecdotal evidence for this claim. If it can be validated, then writing will be confirmed as a distinctive means of learning. Such issues could be pursued further through online research methods such as collecting verbal protocols of writing episodes.

Several limitations to the present research should be acknowledged. First, the writing interval was brief. This was realistic in that a single science class often includes an experiment followed by journal writing. However, in most science programs this would occur in the context of a unit of study consisting of a series of activities related to a single topic. Also, the students in the present study were atypical in that most were highly academically successful but had limited science background. Therefore, the findings might be most directly generalized to settings such as university and college science courses for non-science majors. Further research is needed to examine the relationship between rhetorical structures and learning among elementary and secondary students. Another limitation of this research is that learning was measured by changes in explanations, which comprise explicit, verbal knowledge. This raises the question of how writing affects other kinds of knowledge such as visual representations or procedural knowledge. Finally, the relationships between rhetorical structures and explanatory gains reported here were correlational. These relationships could be further supported by replicating this instructional study with students who do not normally use these rhetorical structures.

Within these limits some tentative suggestions can be made concerning the educational implications of this study. First, it was found that students with moderate levels of prewriting knowledge made explanatory gains. For example, recall from the qualitative analysis in the forces problem, only students who initially recognized the reaction force in the spring trial were able to generate an analogous explanation for the table trial. Conversely, students whose initial explanations were at ceiling were almost always able to apply writing structures validly to the demonstration. Consequently, the relationship between writing and knowledge appeared to be reciprocal: Prior knowledge facilitated writing text with elaborative rhetorical structures, whereas writing with elaborative rhetorical structures contributed to the construction of new knowledge. Instructionally, this means that students who have little knowledge relevant to a given science topic, and who therefore most need to learn about it, may have the most difficulty doing so by writing. This suggests that educators could try to introduce students to the elements of a problem first, then ask them to use writing to construct relationships among these elements. This implication could be tested in future research.

The present study also suggests that educators could familiarize students with elaborative rhetorical structures such as explanation, comparison, and argumentation in order to help them to benefit from writing activities. In the past, writing-to-learn has sometimes taken the form of undirected freewriting, in which students were urged to write down whatever came to mind and were discouraged from planning or revising. In contrast, the present research supports the genre theorists' view that elaborative rhetorical structures contribute to the instructional value of composing (Martin, 1993; Stotsky, 1995). Advanced writers appear to use these rhetorical structures without prompting, but younger and less proficient writers are less likely to do so when reading, writing, and speaking (Chambliss, 1995; Kuhn, 1991; Wright & Rosenberg, 1993). Fortunately, explicit instruction can enhance students' ability to do so (Englert & Raphael, 1989; Sexton, Harris, & Graham, 1998). The question of whether teaching such genres increases students' ability to learn through writing invites empirical investigation.

Finally, it would be tempting to think that writing-to-learn depends on rhetorical structures that students can be taught, then transfer to any problem. However, in the present study both the effectiveness of writing-to-learn and the effects of particular rhetorical structures differed between two science problems. This suggests that it may not be possible to recommend generally effective writing-to-learn strategies. Moreover, it would be untenable to test the innumerable combinations of writing strategies and academic content experimentally. Rather, teachers may need to match writing assignments with curriculum content through conceptual analysis of topics and concepts, or through trial and error. In this case, writing-to-learn will comprise part of teachers' topic-specific pedagogical content knowledge rather than their general pedagogical knowledge.

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Appendix A
Suggestions for Writing

Please check off any suggestions that you choose to follow.

Before writing
- Consider writing a sentence to explain each of the experimental trials.
- Consider comparing experimental trials.
- Consider offering an explanation, then using each trial to argue for this explanation.

While you are writing
- If you run out of ideas, try looking back at the experiment.
- If you run out of ideas, try looking back at what you have already written.
- If any trial surprised you, try to explain it. See if this explanation will fit other trials too.
- Are their any trials that you have not yet written about?

After writing
- Try to add three more sentences.
- Reread what you have written.
- Make sure that you have written exactly what you mean.
- Does what you have written agree with what happened in the experiment?
- Try to add a concluding sentence that summarizes the ideas that you have already written.