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The Construction and Analogical Transfer of Symbolic Visualizations

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Abstract

Two studies explored whether adolescents can and will construct abstract visualizations to structure complex information. Experiment 1 showed that students can structure novel information with visualizations. Seventh-, 9th-, and 10th-grade students were directed to construct visualizations of complex transmission problems in biology (e.g., epidemiology). Two-thirds of the resulting visualizations at each grade level captured the structure of the problems. The 9th/10th graders primarily constructed path diagrams (i.e., directed graphs), and the 7th graders constructed more original visualizations. Experiment 2 showed that students will analogically transfer specific visualizations and will transfer the strategy of visualizing. On pre- and posttests 7th graders solved transmission problems without cues to visualize. During an intervention, students in two treatments constructed and learned visualizations for three problem types. In the Path treatment, one problem type involved path diagrams. In the No-Path treatment an alternate problem type was used as a filler visualization task. Overall, 50% more students used visualizations on the posttest compared to the pretest. Students in the Path treatment analogically transferred the path diagram to the posttest, whereas students in the No-Path treatment spontaneously constructed alternative visualizations. These findings suggest that instruction in visualizing may develop a strategy that students can and will use to understand the structure in complex and novel information.

An important aspect of learning new information is to understand the structure among concepts. There are numerous approaches to help students develop a structural understanding of novel information, including the use of analogies (Polya, 1945), concept maps (Schmid & Telaro, 1990), advanced organizers (Ausabel, 1968), planning (Pea & Kurland, 1987), data organization (Underwood & Underwood, 1987), and illustrations (Allender, 1991). These are general methods, because they can be applied to a variety of informational sources; however, there is limited evidence that students can or will spontaneously use general methods without direction (e.g., Detterman, 1993; Pea & Kurland, 1987; Sweller, 1990). In this article I present evidence that another approach for understanding structure—symbolic visualizing—may provide a general-purpose strategy that students can and will use for novel information.

Symbolic visualizations—visualizations that do not resemble their referents (Cummins, 1989)—are abstract, nonsentential representations of structure. For example, to convey the cyclical nature of photosynthesis and respiration one could draw a path diagram (i.e., a directed graph). Like drawing an analogy, a good visualization can reveal structure in novelty (Gentner, 1989; Novick, 1990); however, unlike analogies, symbolic visualizations explicitly indicate structure (Breuker, 1984) and are well suited to numerous relations (Bertin, 1983). The utility of

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visual representations for indicating complex structure is demonstrated by the successful histories of visualizations such as Cartesian graphs, Venn diagrams, trees, and tables (Sless, 1981; Tufte, 1990). Additionally, as shown by the growth of scientific visualization (Pickover, 1991), the externalized process of visualizing provides a means for progressively refining and assessing structural understanding (Macdonald-Ross, 1977). If students have an opportunity to experience the utility of visualizing, they may incorporate visualization as a general method for understanding complexities.

Because of the utility of symbolic visualizations, students at all ages are taught numerous visual conventions to help illuminate relationships. However, this instruction typically lacks an important component of visualizing. Students are given prespecified visual conventions, and consequently they rarely go through the process of deciding which representational features capture the structure of the information at hand. This is a significant omission because people often face novel information for which no one has provided a ready-made visual framework. The current research shows that if encouraged and given the opportunity, students have the competence and inclination to construct visualizations on their own.

The current research may be contrasted to relevant research in spatial learning strategies and analogical transfer. Numerous spatial learning strategies like Vee mapping, schematizing, and concept mapping have been examined for a variety of purposes and effects (for a sample see Holley & Dansereau, 1984). These investigations differ from the current investigation in that they each examine a single formalism. For example, in concept mapping, students construct or are given visual networks that associate related concepts (e.g., Rewey, Dansereau, Skaggs, Hall, & Pitre, 1989). A limitation of concept mapping is that it relies solely on the network formalism. Students may further benefit by constructing visual representations that are more closely tailored to the inferences they may draw from a particular body of information. For example, consider information about disease transmission. In this case, an appropriate visual representation is a path diagram. A path diagram can facilitate inferences about who is at risk from infection. Next, consider information about diseases and their symptoms. In this case, one appropriate representation is a matrix, because the cross indexing of diseases and their symptoms supports diagnosis. Although one could represent both disease transmission and disease symptoms in a network, some visualizations (e.g., a matrix) are more appropriate for some inferential goals (e.g., diagnosis) than others (Tufte, 1990). As has been pointed out by cognitive scientists and educators (e.g., Anderson, 1978; Holland, Holyoak, Nisbett & Thagard, 1989; Larkin & Simon, 1987; Macdonald-Ross, 1977), a representation of structure cannot be evaluated independently of its use.

Like research on analogical transfer, the current research explores the illumination of structure by looking outside the original information itself (i.e., looking to analogs or visualizations). However, the current work begins from a different vantage. Typically, analogical transfer studies examine the conditions under which people can remember the structure of a previous example to illuminate a target problem (e.g., Gick & Holyoak, 1980, 1983). Although memory is clearly important and should be enhanced by the spatial explicitness of visualizations (e.g., Yates, 1978), I begin from the premise that people will better retrieve appropriately structured examples if they have a strategy, like visualizing, for understanding the structure of a target problem (Beveridge & Parkins, 1987). Thus, the primary focus here is on whether people can and will construct a visual representation to structure a target problem (Bamberger, 1978; Karmiloff-Smith, 1979).

To suggest that visualizing instruction could endow students with a general strategy, it is necessary to produce three lines of evidence. One, students must have the competence to construct original visual structures. If visualizing is a useful general strategy, students should be able to use it even in situations where they do not have an appropriate visual formalism in their arsenal, or where they do not initially understand the informational structure well enough to select an appropriate formalism. Two, students should analogically transfer an appropriate visualization for a body of information. If students are to build on instruction in visualizing, they must be able to match learned visual structures to new information. Three, students must spontaneously use visualizing as a methodology even when there are no prompts to do so. If students are to profit from the strategy they must be inclined to use it.

If the following studies evince these three points, then it will be worthwhile to ask further pragmatic questions such as whether the student-generated visualizations actually improve comprehension and problem-solving performance. However, at this stage of research, it is important to note that the questions involve competence and inclination, not performance. For example, a student could create an original visualization but mistakenly omit information. Moreover, as students first learn to construct visualizations, they may be inefficient at using them to draw specific inferences. Although performance issues are important in their own right, the current question is whether the students will even construct a visual representation of structure that makes it possible to reach the point of making errors of omission and faulty inference.

Experiment 1

Experiment 1 explored whether secondary school students can construct visualizations that represent the structure of complex information. The students' task was to "lay out or visualize the information in the sentences in such a way that it could help in answering the questions." The information was about the transmission of effects throughout a natural pathway such as energy through a food web.

For the transmission problems an appropriate visualization integrates the sentential information using three structural features. It indicates the *direction* of transmission such that one can order the cause and effect. It indicates *one-to-many* relationships such that one can infer that a single cause has multiple effects. Finally, a good visualization includes a provision for *many-to-one* relationships such that one can infer that a single effect has multiple causes. The author determined that these three features represent the minimal structure needed to solve the transmission problems. Analysis by two independent researchers concurred with this analysis. For example, the problems do not require a distinction between necessary and sufficient causes, and thus a visualization does not need to indicate this distinction. On the other hand, if a visualization omits the many-to-one relationship, it cannot help with problems such as what organism eats the most types of organisms. Although one could reason about this problem without a many-to-one visualization, or without a visualization at all, the presence of this and the other two features indicates a successful construction of a model of structure through visualizing (Albarn & Smith, 1977).

Three factors were crossed to explore potential influences on visualizing. The first factor was the students' familiarity with the biology topics. If visualizing is an effective structuring tool for novel information, students should be able to construct visualizations for both familiar and unfamiliar topics given that the topical information has the same structure. The second factor was grade level. Classroom teachers indicated that 9th/10th-grade students had more experience with path diagrams than 7th graders. Because of the older students' experience, they would provide first evidence of analogical transfer if they chose to use the appropriate formalism of path diagrams. In contrast, because the 7th graders had less experience, they would provide a good population for testing whether students can construct original, well-structured visualizations. The final factor was whether students worked alone or in pairs. Prior research has shown that dyads have an inclination to construct more abstract representations than do individuals (Schwartz & Black, 1993a). By including the grouping factor, it was possible to see if dyads also created visualizations with more structure than individuals.

Method

Subjects. Fifty-two 7th graders in three life science classes at a middle school and 39 9th/10th graders in two biology classes at a high school participated as part of their regular class day. Both schools were in suburban New York and in their final month of instruction. The life science students all had the same teacher, as did the biology students.

Materials. Eight experimental packets covered four topics familiar to all students: food webs, water cycles, pollination, and cause and effect; and four topics unfamiliar to all students: DNA tracing, epidemiology, protein pathways, and demographics. Familiarity was determined in discussions with classroom teachers. On the first page of each packet was a description and an example of the basic concepts. Below the example there were a number of sentences that described the relations between lettered entities. The second page of the packet provided space for the visualization. The third page had a reading comprehension question and two inferential questions based on the information provided in the relational sentences. Appendix A shows one packet collapsed onto a single page.

Design. Each student or dyad received one of the eight packets. Three factors were crossed in an exploratory between-subjects design. One factor was the familiarity of the biology topic. A second factor was student grade levels—7th graders and 9th/10th graders. The third factor was student grouping such that some students worked in pairs and some worked individually. Within intact classrooms, students were randomly separated into problem-solving dyads and individuals so that there were approximately 20 individuals at each grade level. For the 7th graders, there were 20 individuals and 16 dyads. For the 9th/10th graders, there were 19 individuals and 10 dyads.

Procedure. On day 1 all students were randomly paired and played prisoners' dilemma (Rapoport & Chammah, 1965) to encourage collaborative efforts in the dyad condition. On day 2 students were asked to work alone or with their partners of the previous day. Packets were distributed to ensure relatively counterbalanced distribution of the eight topics across the grade and grouping factors. The experimenter, reading from a script, told the students that they should read the first page and then try to lay out or visualize the relations. They were told that a good representation should help them answer the questions on the third page. Students could move between pages.

Coding

Before evaluating the coding scheme, the reader may benefit by examining the student constructions presented in Figure 1. Figure 1(a) shows a path diagram. Figure 1(b) is also a path diagram, except that it includes what is being transmitted from each letter. For example, the B

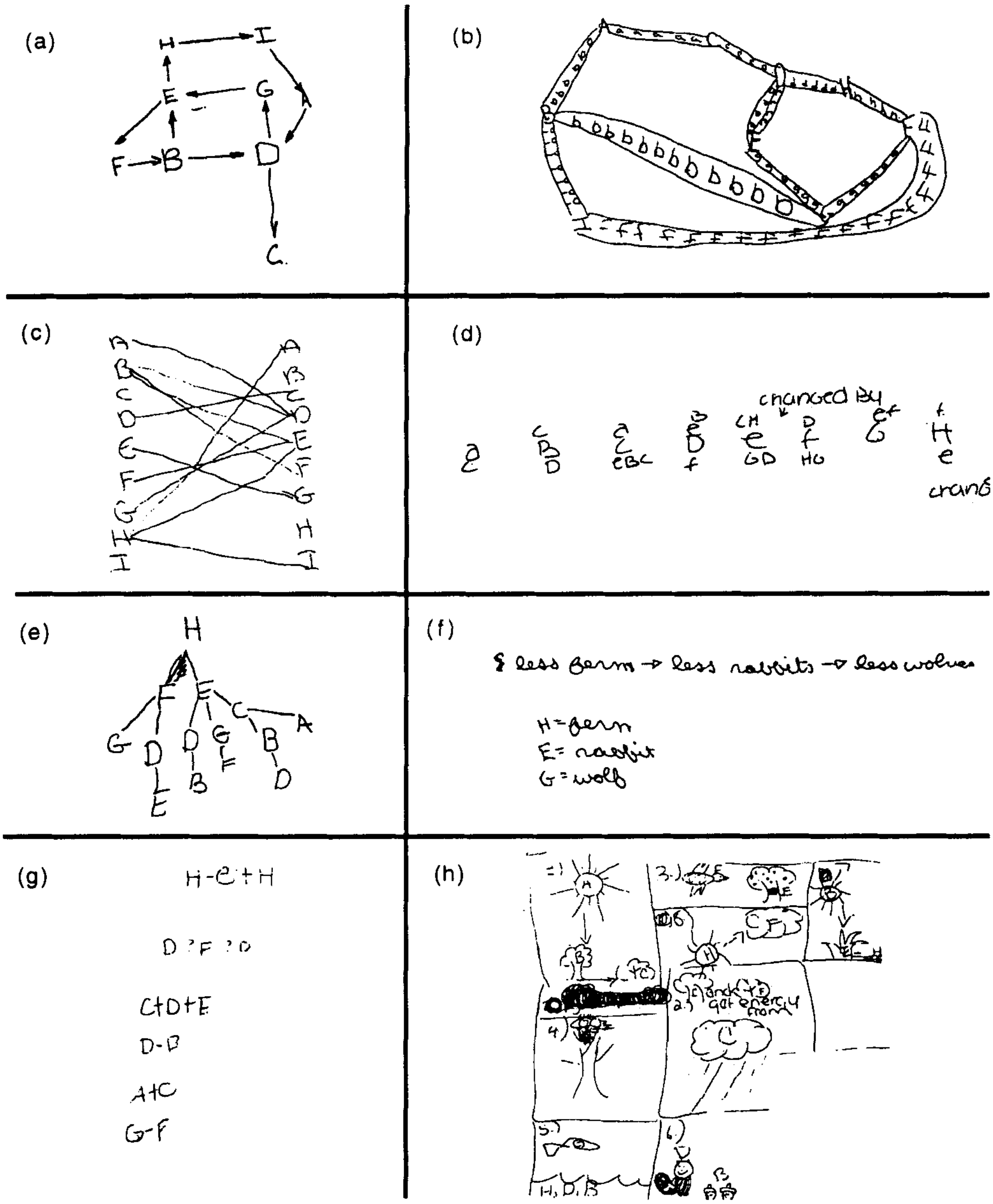

Figure 1. A sample of visualizations constructed for transmission problems.

node is transmitting small letter b's to the A and G nodes. Figure 1(c) also indicates the directional, one-to-many, and many-to-one structure of the information. It can be read as either "the left side gives to the right side," or, "the right side gets from the left side." Although more cumbersome than a path diagram, this representation does have the advantage that one can use the alphabetical indexing to locate a specific letter. Figure 1(d) is also an innovative formalism in which the corresponding causes and effects are placed above and below each letter. The tree structure in Figure 1(e) indicates direction and one-to-many relationships according to the convention of reading downward. However, tree structures do not have a direct many-to-one representation and must repeat the letters. For example, three letter D's are needed to represent that F, E, and B can affect D. Although this redundancy is not a catastrophic weakness because the information can still be retrieved, it does increase the chances of overlooking connections. For example, one is less likely to notice that F, D, and E are in a cycle. Figure 1(f) is an example of a solution that only shows the direction of connection. Figures 1(g) and 1(h) do not integrate the information into a single structure. In both cases, each equation or box represents a transcription of a single informational sentence. Figure 1(h) has the further disadvantage of an inconsistent, concrete interpretation of the letters. For example, D is represented as water in one box and as a squirrel in another. The attempt to make the letters semantically specific in Figures 1(h) and 1(f) is intriguing in that the original sentences do not indicate specific referents. For example, a D did not refer to something like a dog. In these cases, one can see that the student was trying to draw an analogy to concrete referents.

Rather than considering all possible graphical features (e.g., Bertin, 1983), three categories provided a parsimonious measure of student competency at visualizing transmission problems. Visualizations were coded according to three criteria. First, for the direction of a connection, a visualization could be coded as having no direction [Figures 1(g) and 1(h)] an implied direction [Figures 1(c) and 1(e)], or an explicit direction [Figures 1(a), 1(b), 1(d), and 1(f)]. Second, for the one-to-many relationships, the category was dichotomous, indicating the presence [Figures 1(a)–1(e)] or absence of structural provisions. Third, for the many-to-one relationships, a visualization could have no structural provision [Figures 1(f)–1(h)], it could represent this relationship by using a letter more than once [Figures 1(c)–1(e)], or it could be a path diagram [Figures 1(a) and 1(b)]. A fourth dichotomous category was constructed to provide a summary measure. It indicates whether a visualization included some structure in each category [Figures 1(a)–1(e)]. Thus, each visualization received four codes, one per category. Two independent coders, trained on pilot data and coding separately, had 97% agreement without systematic biases. Disagreements were resolved by consensus.

Results

Overall, 66.2% of the visualizations included structural features for all three categories. This is well above the 22% one would expect had categorizations been randomly assigned, $Z_{(65)} = 8.45$, $p < .01$. Table 1 displays the categorization percentages broken down by the three factors of the experiment. To evaluate the dependence of the three visualization features on the crossed factors of familiarity, age, and grouping (individual/dyad), a multivariate analysis of variance was conducted (Cliff, 1987). A multivariate analysis is preferable because of associations among the categories (e.g., path diagrams always included one-to-many features). There were no strong effects as a result of the topic familiarity, $F(5,53) = 0.76$, $p > .55$, the grouping, $F(5,53) = 1.12$, $p > .35$, or any of the interactions, $F(5,53) < 1$. The only significant effect resulted from the grade factor, $F(5,53) = 4.23$, $p < .01$. A subsequent univariate analysis located this effect in the many-to-one category, $F(1,57) = 11.98$, $p < .01$. The 9th/10th graders predominantly used path diagrams to indicate the many-to-one structure, whereas the 7th graders tended to use letter repetition methods.

Discussion

Approximately two-thirds of the students at both grade levels were able to construct competent visualizations. For the 9th/10th graders, the most frequent visualization was a path dia-

Table 1
Percentages of Visual Structures Broken Down by Main Factors

	Topic familiarity		Grouping		Grade	
	$n = 32^a$ *Low*	$n = 33$ *High*	$n = 39$ *Indiv.*	$n = 26$ *Dyad*	$n = 36$ *7th*	$n = 29$ *9th/10th*
Direction						
None	15.6	15.2	20.5	07.7	13.9	17.2
Implied	12.5	27.3	12.8	30.8	19.4	20.7
Explicit	71.9	57.6	66.7	61.5	66.7	62.1
One-to-Many						
None	21.9	15.2	23.1	11.5	13.9	24.1
Included	78.1	84.8	76.9	88.5	86.1	75.9
Many-to-One						
None	25.0	27.3	28.2	23.1	25.0	27.6
Redundant	43.8	57.6	48.7	53.8	66.7	31.0
Path Diagram	31.3	15.2	23.1	23.1	08.3	41.4^b
All Three Structures[c]						
No	34.4	33.3	38.5	26.9	30.6	37.9
Yes	65.6	66.7	61.5	73.1	69.4	62.1

[a]Each dyad serves as a single *n*.
[b]$p < .01$, many-to-one by grade level.
[c]Includes some provision for all three structures.

gram. One interpretation is that the 9th/10th graders analogically transferred this formalism from prior instruction. The next experiment investigates the analogical transfer of visualizations more rigorously. In contrast to the 9th/10th graders, the 7th graders rarely used path diagrams. Instead, many of them constructed ingenuously original visualizations. These results suggest that students can use visualizing as a general strategy for representing the structure of transmission problems.

It should be noted that the coding scheme used here was based on the end results of the students' efforts at a novel task and therefore may not accurately reflect some students' nonexplicit understandings. Additional research is needed to test the reliability and validity of the coding as well as the implications for assessing and predicting student understanding and performance. For example, it may be that some students understand the structure of the problems quite well but are incompetent with the visual medium. As such, the coding approach should be viewed as exploratory and should not be exported inflexibly. Nonetheless, for the current purposes the coding gained credibility from random exit interviews. The students' descriptions of why they included visual features corresponded to the codings given to the visualizations.

Subsequent research should test the generality of the current results. For example, the lack of a topic familiarity effect is an important finding given the repeated evidence of domain-knowledge effects in reasoning (e.g., Johnson-Laird, Legrenzi, & Legrenzi, 1972; Mayer, 1976). If visualizing is fairly independent of domain familiarity, then visualizing is a truly general problem-solving strategy. To clarify this result, subsequent studies should directly measure students' domain knowledge and use more grade levels, classrooms, and students. Similarly, additional informational structures should be used as stimuli. This would test whether students are equally competent at visualizing other information structures (e.g., cross indexing or quantitative) and structures that may be unknown to the students (e.g., recursive structures).

In addition to investigating the extent of visualizing competence, there needs to be an examination of the process of constructing structure through external images. There is an enormous and varied literature on the interpretation of external images (e.g., Gombrich, 1969; Mandl & Levin, 1989; Sless, 1981), and a growing literature on the construction of internal images (e.g., Kosslyn, 1980; Marr, 1982). However, there has been minimal investigation into the process of constructing of external images. For the most part researchers have looked at completed visualizations to make developmental and cross-cultural claims (Cox, 1992; Tversky, Kugelmass, & Winter, 1991). Examining the constructive process may better illuminate the potential applications of visualizing as well as the basic issues of how people construct structure (Bower, Black, & Turner, 1979). For example, consider the 7th graders who were able to create original representations. They apparently did this by taking prior conventions and recasting their properties to fit the structure of the problem. In Figure 1(c) it may be seen that the student made a visualization similar to the vocabulary tasks where one matches a word and its definition with a connecting line. To modify this formalism, the student removed the constraint of a one-to-one correspondence between items and repeated items on both sides of the table. Consequently, one can read back and forth to make chains of inference. This process of recasting a prior formalism around a new set of relationships may be a fairly general approach to constructing structure (Schwartz & Black, 1993b). By understanding the preconditions and catalysts of structure construction, it may be possible to design a sequence of instruction that capitalizes on students' ability to build structure through visualizing.

Experiment 2

In Experiment 1 students constructed adequate visualizations when directed to do so. Will students also spontaneously apply visualizing to structure novel problems? One issue is whether students can evaluate information and draw an analogy to an appropriate visualization. A second issue is whether students can transfer the strategy of constructing a visualization when they cannot draw upon a visual analogy.

In Experiment 1, 9th/10th graders used path diagrams more than 7th graders. To pursue this result, the current experiment tests the possibility that the more frequent use of path diagrams resulted from an analogical transfer. Prior laboratory research by Novick (1990) has shown that college students with high SAT scores can use visualizations as a source analogy for a body of information. Given exposure to a matrix in one domain, subjects transferred this representation to another domain 54% over baseline. Novick argues that this high transfer rate came about because knowledge representations transfer better than the procedural knowledge[1] that is usually used to test for analogical transfer. One might further speculate that the mnemonic benefits of visual presentations also facilitated the transfer (Pavio, 1986; Shepard, 1967; Standing, 1973). The question asked here is whether adolescents in a classroom setting will also make the analogical transfer of visual conventions.

The second issue is whether the methodology of visualizing transfers. In the previous investigation, students were directed to make visualizations. Although they showed competence at this task, this does not mean they would visualize of their own accord. The lack of spontaneous visualizing would not be surprising, because visualizing involves the extra step of creating a visual mediator. However, it is possible that students will recognize the utility of visualizing and will transfer the idea of mediating their problem solving with visualizations. This would be a valuable finding given the limited number of studies that have documented the transfer of general strategies (e.g., Palinscar & Brown, 1984).

Figure 2 presents an overview of the two treatment, pre–post experimental design. On the

TREATMENT	TEST	INSTRUCTION			TEST
	Day 1	*Day 15*	*Day 16*	*Day 17*	*Day 35*
PATH	Pre-Test[a]	Matrices	Path Diagrams	Permutation Lists	Post-Test
NO-PATH	Pre-Test	Matrices	Cartesian Graphs	Permutation Lists	Post-Test

[a] Pre- and posttests use path-type problems in both conditions.

Figure 2. Two-treatment, Pre-/Posttest experimental design.

pre- and posttests, students in both conditions solved transmission problems as a regular class activity. Appendix A shows one of the tests used. The students received no hints to use visualizations and received no feedback on their performances. During each of the three days of the intervention, students constructed an original visualization to solve a problem. Afterwards the experimenter taught a canonical formalism for that type of problem, and students practiced it with an isomorphic problem. On each day, a different informational structure and visualization was used. The two treatments differed on the second day of instruction: the Path treatment received instruction in path diagrams, and the No-Path treatment received filler instruction in Cartesian graphs for trend analysis.

How might the two experimental conditions influence performance on the posttest relative to the pretest? In the Path treatment, where students construct path diagrams, the students should be inclined to use a path diagram on the posttest. They should find the analogy between the structure of the problem and the path diagrams. In the No-Path treatment, the students should use path diagrams at a lower rate, because they had no instruction on this formalism. Because this experiment relied on 7th graders, the rate of path diagram use in the No-Path treatment should be comparable to Experiment 1. Although few No-Path students should use path diagrams, the visualizing strategy may transfer. If this occurs, No-Path students should attempt to visualize, although not with path diagrams.

The experiment was designed to minimize contextual reinstatement cues and perceived task demands that might confound evidence of analogical transfer. For example, the tests and intervention were separated by two weeks, and the experimenter who taught the intervention was not present during testing. To further minimize incidental retrieval cues, perceptual and semantic features of the tests and the instructional materials were varied (compare the test form in Appendix A with the instruction form in Appendix B). For example, to prevent transfer on the basis of the semantic similarity of the test and instructional items, the path instructional materials used pollution and food webs, and test materials used hormones and epidemiology. If both materials had used similar cover stories, this similarity could have served as a retrieval cue (Ross, 1987).

Method

Subjects. Suburban New York 7th graders from two average-ability life science classes with the same teacher participated in the experiment as part of their regular instruction. Because of absences and the use of intact classrooms, the usable sample was 14 students in the Path treatment and 24 students in the No-Path treatment.

Materials. Five isomorphic pairs of packets employed four informational structures. The four structures were selected for the experiment on the basis of unfamiliarity and potential learnability (as indicated by the teacher). For the instruction, the visualization structures and topics were matrices, that is, fish habitats, disease symptoms; path diagrams, that is, pollution spread, food webs; Cartesian graphs, that is, plant growth, weather patterns; permutation lists, that is, migration orders, pecking orders. An additional pair of path diagram problems, isomorphic to one another but not to the intervention materials, were constructed for the pre- and posttests using the topics of hormones and epidemiology. The test and intervention materials were topically and perceptually different. A particularly important difference was that the instructional materials provided an explicit space for visualizing and the tests left space at the bottom of the page for solutions.

Design. A two-treatment, pre/posttest design, illustrated in Figure 2, varied the second day of instruction between the two groups. Path treatment students received instruction on path diagrams, and the No-Path students received filler instruction on Cartesian graphs. The test forms were counterbalanced by treatment and test.

Procedure. Two weeks before and after the experimenter taught the intervention, the students worked for 20 minutes on the pre- and posttests as a part of a weekly problem-solving day. During the three days of the intervention, each day's instructional cycle worked as follows: Students received a problem sheet that asked them to construct a visualization that would help solve the problems. After 20 minutes the experimenter reviewed selected student solutions and offered a canonical approach (i.e., matrix, path diagram, etc.). The students practiced this approach on an isomorphic problem.

Results

Pre- and posttests were coded as to whether students constructed a path diagram, made a different type of visualization, or did not make any representation. Table 2 shows the results

Table 2
Visualizing Percentages by Treatment and Pre-/Posttest

	Path treatment (n = 14)			No-Path treatment (n = 24)			
	No visuals	Path diagrams	Other visuals	No visuals	Path diagrams	Other visuals	Pooled Treatments Path + other visuals
Pretest	100.0	00.0	00.0	92.9	00.0	07.1	02.6
Posttest	35.7	50.0	14.3	54.2	08.3	37.5	52.6

broken down by test and treatment. Two coders, blind to treatment and working separately, had 100% agreement. The alternate test forms had no differential effect. A comparison of the coded category frequencies from the two test forms did not approach significance, $\chi_{(2)}^2 = 0.42$, $p > .8$.

The hypothesis that students would adopt the visualizing strategy was strongly supported. Pooling across treatments, 2.6% of the students used visualizations on the pretests, whereas 52.6% used visualizations on the posttests. A within-subject comparison of the percentage change (Walker & Lev, 1953) shows this to be a reliable difference, $\chi_{(1)}^2 = 19.0$, $p < .01$. Although the total percentage of visualizations is descriptively larger in the Path than No-Path treatment at posttest (64.3% versus 45.8%, respectively), this difference does not reach significance; $\chi_{(1)}^2 = 1.21$, $p > 0.25$.[2] Thus, the increase in visualizing occurred across both treatments.

The hypothesis that experience with path diagrams leads to their analogical transfer was supported. 50% of the path treatment students used path diagrams on the posttest compared to 8% of the No-Path students. A comparison of the percentages of posttest path diagrams in the two conditions is significant, $\chi_{(1)}^2 = 8.49$, $p < .01$. A second analysis that controls for the larger, overall rate of visualizing in the Path treatment also shows the effects of the path diagram instruction. Considering only those students who used visualizations, 77.8% of the visualizers from the Path treatment used path diagrams compared to 18.2% in the No-Path condition, $\chi_{(1)}^2 = 7.1$, $p < .01$.

A frequent question is whether the visualizations helped the students answer the questions. Pooling across the conditions, constructing a path diagram yielded a 233% gain on the posttest questions, other visualizations yielded a 205% gain, and no visualizations yielded a 150% gain. However, the influence of visualizations on problem-solving success cannot be definitively addressed by this or the previous experiment. First, the questions were designed to make the task purposeful rather than to reveal differences in problem solving. Second, student ability may be an underlying variable that caused both the more appropriate visualizations and the better answers.

Discussion

In both treatments, there were large increases in the frequency of visualizing from pretest to posttest. Evidently the students acquired the idea that visualizing is worthwhile. This interpretation gains force from the No-Path treatment, where the increase in visualizing cannot be ascribed to analogical transfer. There are, however, a number of factors that could have led to the transfer of visualizing. For example, on the negative side it may have been that the similarities between the intervention tasks and the posttest were salient in contrast to other classroom activities. On the positive side, regardless of whether or not the students directly associated the posttest problems with the instruction, they still chose to construct a visualization two weeks later, whereas they had not previously.

The Path treatment students used path diagrams significantly more often than the No-Path students. The favored explanation is that the Path students made an analogical transfer whereby they found the analogy of structure between the posttest and the visualization they had learned previously (Novick, 1990). A contrasting explanation is that the students first retrieved the intervention problems and only afterwards thought to make path diagrams like they had for the intervention problems (e.g., Gick & McGarry, 1992). Although this competing explanation cannot be refuted, there are reasons to question it. First, topic differences minimized opportunities for a match between the content of the intervention and posttest. Second, the problem pages on the other days of the intervention involved the same perceptual features as the path problems. If it were the perceptual quality of the problems or their presentation that led to the transfer, one should not expect the dominant use of the path diagrams. Third, the students in the No-Path condition made visualizations without having received analogously structured materials. This suggests that these students were trying to analogize to general visual structures rather than to a specific prior problem in the No-Path condition. One may tentatively conclude that students in the Path condition were also trying to analogize to a general visualization. In their case, they found the posttest problems analogous to the path diagrams they had previously learned.

A number of questions remain to be answered about the transfer of visualizing activity and the analogical transfer of specific visualizations. For example, would students transfer the idea of visualizing to more remote tasks like compiling data from a real biology experiment? Did the intervention's employment of isomorphic training pairs lead to a schema induction that was responsible for the high rate of analogical transfer (e.g., Gick & Holyoak, 1983)? Was it the constructive nature of the instruction that ensured transfer appropriate processing (Morris, Bransford, & Franks, 1977)? For example, if students merely practiced prespecified visualizations, rather than having the opportunity to construct their own first, would they have transferred the constructive activity at the same frequency (Bransford, Franks, Vye, & Sherwood, 1989)? Further research should illuminate the whys and whens of students' facility with visualizing.

General Discussion

Through two studies students revealed a competence at constructing and an inclination to transfer explicit, visual representations of structure. Students drew the analogy between the general formalism of path diagrams and a novel body of information (Experiment 1, 9th/10th graders; Experiment 2, Path treatment). Moreover, even when they could not recall an ideal formalism, students created visualizations to meet the structure of the information (Experiment 1, 7th graders). Finally, when encouraged through minimal instruction, students spontaneously used visualizations two weeks later to understand the structure of a novel problem (Experiment 2, No-Path treatment). The combination of these results suggests that visualizing offers a promising, general problem-solving strategy: students are relatively good at it and are willing to use it. Although conclusions based on these exploratory experiments are provisional pending further investigation, the results suggest directions for further exploration into a new classroom practice.

One possible classroom practice is to use constructive visualizing as an introduction to new material. Rather than giving students premade organizers (Ausabel, 1968) or predefined conventions such as concept maps (Novak, 1991), students would be encouraged to construct their own visualizations. A teacher would provide students with a small part of the information from a forthcoming lesson. The students' task would be to visualize the information in such a way that the visualization would help answer a set of questions. The key element in designing such a task is to organize the information and the questions such that it would scaffold and encourage a visualization with the appropriate structure. For example, consider an instructional unit on biological classification. A traditional approach might be to give students an overview of all the classifications and ask questions about their definitions; however, this would not focus students' visualizing on the basic structure of biological classifications. A preferable approach would present information about common and differing features in several organisms, and then would ask questions about set and subset relations among the organisms. This latter approach should lead to the construction of a hierarchical structure that serves the general inferential goals supported by biological taxonomies, producing three positive results. First, it should promote visualizing as a general strategy for structuring information to meet specific inferential goals. Second, the constructions should yield a structured and purposeful framework for organizing and remembering subsequent information (Gelman, Massey, & McManus, 1991). Finally, students should be more receptive and appreciative of a conventional tree structure after having experienced the issues involved in constructing a visualization that supports inferences about hierarchical relations. In sum, giving students the chance to experience the power of the visualizing strategy and to experience the power of specific visualizations seems to be an excellent method for encouraging students to construct structure out of complex novelty.

Appendix A: A Pre-/Posttest Form from Experiment 2

EPIDEMIOLOGY Name ______________________

Diseases travel from group to group of people in very predictable ways. For example, in a nursery school, if one kid has a flu it is a safe bet that a number of kids in the class will be infected by the flu. And if the kids catch the flu, there is a good chance the parents will also be infected. And, if the parents catch the flu, they may infect all the people in their neighborhood.

Knowing the way a disease travels from group to group can be very important. It has helped to control the spread of killer diseases like measles, tuberculosis, and AIDS. To see how important this knowledge can be, imagine that there is a new disease that is starting to spread in New York City. Also imagine that there is only enough vaccine to protect 500,000 people from the disease. How do you decide who should get the vaccine? Well, if you know who is most likely to get the disease next, then the decision is easy. You give it to the group that would get the disease next. If this next group cannot be infected by the disease, then they cannot spread it either. For example, if the kids in the nursery school cannot catch the flu, then they cannot pass it on to their parents. In this way, you can stop a disease before it infects the rest of the city. The epidemiologists who study the movements of diseases play an important role in the health of our society.

Here is a list of facts about how one disease travels between different groups of people. Use these facts to try to answer the four questions below.

Group Z can pass the disease to groups Y and X.
Groups V and U can get the disease from group X.
Group U can catch the disease from group V.
Group T can infect group R.
Group T can pick up the disease from S, W and Y.
Group Y can pass the disease to group W.
Group Y can infect group V and group V can infect S.
Group S can be infected with the disease by group U.

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1. Imagine that you find out that group T has the disease. What other group or groups should you prepare for the disease?
2. One year the disease started with group Z and ended up infecting group R. Only the groups that helped to pass the disease from Z to R caught the disease. What is the most number of groups that could have been infected as the disease was passed from group Z to group R? (Do not count Z and R.)

3. Recently, a number of people in group Y caught the disease when travelling to Asia. Up until now, nobody has had the disease this year. However, you know that group Y will spread the disease to other groups. What group or groups of people do not need to worry about catching the disease that Y now has.
4. Which group can directly infect the most other groups without having to pass the disease onto any groups in between?

Put all your solutions on this paper. Do NOT use another sheet of paper.

Appendix B—A Path Diagram Instructional Form from Experiment 2

Biologists Study Food Chains to Protect Organisms

Living things need energy. Where does the energy come from? For almost every organism, this energy comes from the sun. Of course, this does not mean that people can sit in the sun instead of eating. People get solar energy by being part of a food chain. In a food chain, plants make food from the sun, animals eat plants, and other animals eat these animals. In this way, energy from the sun is passed along a chain of organisms.

In different ecosystems, there are different food chains. For example, in the ocean, plankton make food from the sun, shrimp eat the plankton, and salmon eat the shrimp. On land, corn is made from the sun, chickens eat the corn, and people eat the chickens. These two examples are very simple. But food chains are often very complicated and make a food web. For example, people can eat corn as well as chickens. And, people can eat the pigs that also eat corn. A food web occurs when several food chains are tied together.

A good example of a complicated food web comes from the Muzumbi Jungle. In this jungle, the Trindals and Sandies can each provide energy for Dazings. Rondos and Sandies get energy from the Popo. The Faltings can get energy from the Rondos. Dazings are a source of energy for the Gostles. The Gostles can get their energy from the Faltings. Finally, the Trindals can acquire energy from the Rondos.

This is a complicated food web. But knowing how it works can be very important. Biologists who study food chains use this knowledge to save the animals and plants in the food chain. Imagine that you are in charge of keeping the Muzumbi Jungle alive.

1. What organism or organisms can actually eat the most other organisms?
2. How many different ways can energy get from the Popo to the Gostles?
3. There is one organism that you must protect. If this one organism dies, all the other organisms in the food web will eventually die. Which organism must you protect at all costs?
4. One year all the Trindals are exposed to some very dangerous pollution. This pollution gets passed along the food chain because other animals eat the Trindals. Which animal or animals will eventually consume some of this pollution?

- PUT YOUR VISUALIZATION HERE -

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Notes

[1]Procedural knowledge, in this case, refers to the steps one takes to solve the problem rather than the representation that supports these steps.

[2] Because of the limited variance in pretest scores, treatment comparisons only use posttest scores.

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